INSTITUTO DE PESQUISAS TECNOLÓGICAS

## COMUNICAÇÃO TÉCNICA

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# Validation of a novel lifting-line method for properller design and analysis

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**Gustavo Roque da Silva**
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# Validation of a Novel Lifting-Line Method for Propeller Design and Analysis

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# Overview

Introduction

Mathematical Formulation

Results

Conclusion & Future Work

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# Introduction

Knowledge in the emission estimates for **greenhouse gases**;

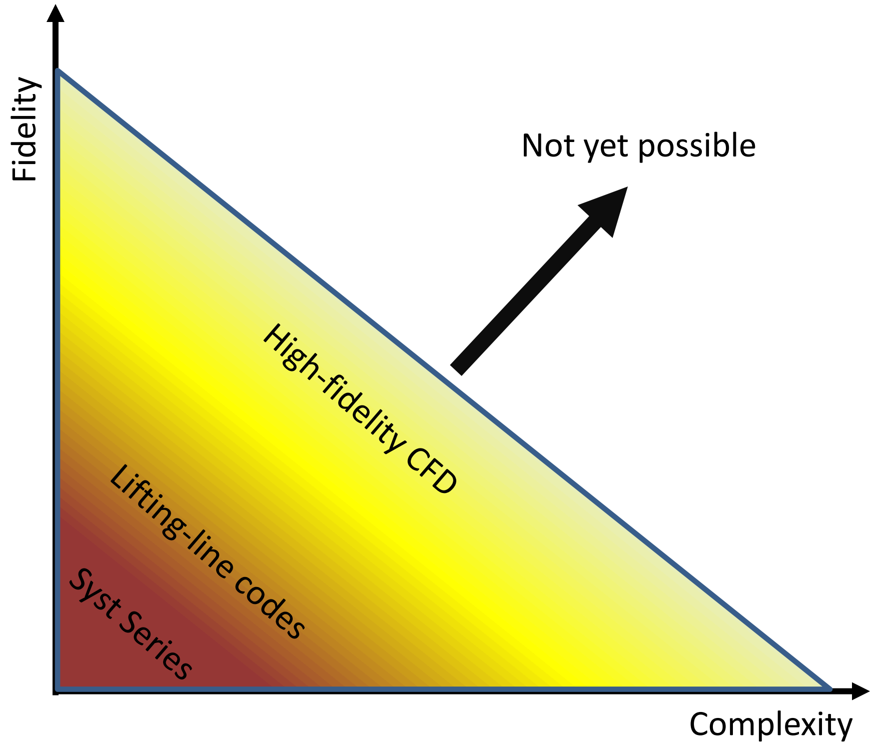
- Efficient ships (**propellers**);
- Compromise $\mathrm{K_T}$, $\mathrm{K_Q}$, $\sigma$;

Tools for **design** and **analysis**;

- Systematic series;
- **Lifting-line theory**;
- Lifting-surface theory;
- CFD (Eulerian formulations);

Development of a **novel** Propeller Lifting-Line **formulation**;

- Originally from Wing lifting-line;
- Adapted to the propeller case;



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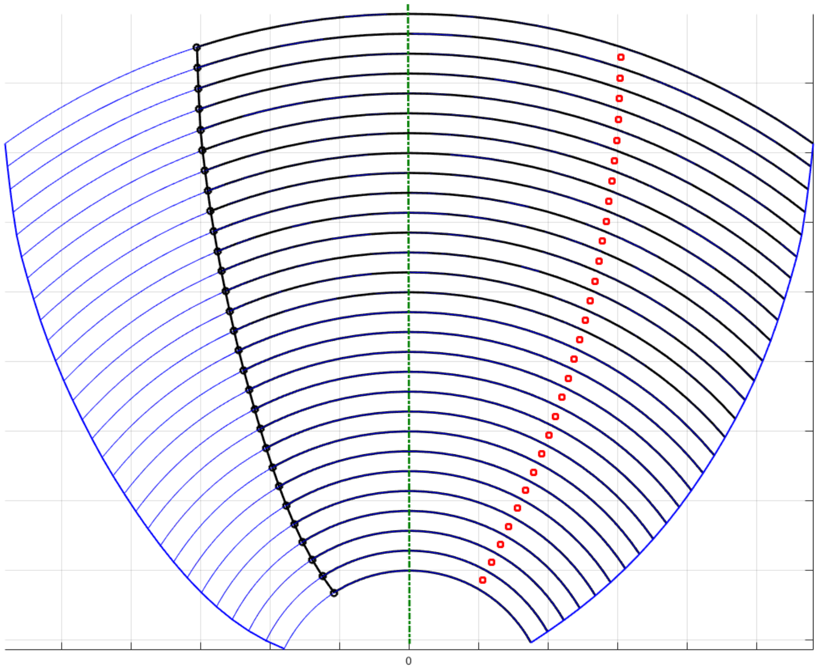
# Mathematical Formulation I
# General

**Novel** Propeller **LL**;

+ Adaptations **from** modern **wing LL**;
+ Close to Helical HSV;
  - **Numerical expressions** using superposition;
+ **Force** Equivalence **+ No flux (**Pistolesi**)** Boundary Condition (PBC);
  - More **general** geometries;
  - **Nonlinear** (viscous) **effects** on $K_T$, $K_Q$, $\beta_w$;

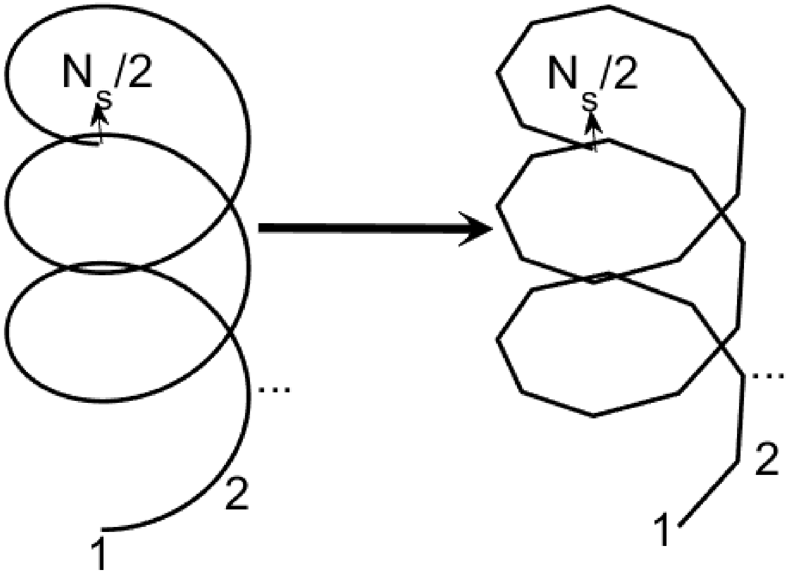


# Mathematical Formulation II
# Horseshoe vortex

**No analytical** expression;

+ Series of **straight segments** (of velocity $\vec{V}_{SS,i,j}^{b_i b_j}$);
+ Velocity of each horseshoe ($\vec{V}_{HS,i,j}^{b_i b_j}$,)

$$\vec{V}_{HS,i,j}^{b_i b_j} = \sum \vec{V}_{SS,i,j}^{b_i b_j}$$



# Mathematical Formulation III
# Pitch angle

HSV shed with **pitch angle** $\beta_{BV,\#,i}^{b_i}$.

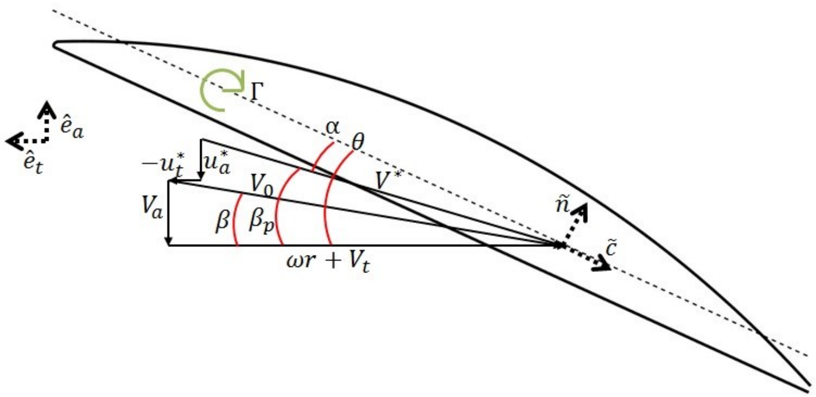
**Linear**:

$$\beta_i^{b_i} = \tan^{-1}\left(\frac{\vec{V}_{P,i}^{b_i} \cdot \vec{e}_{n,i}^{b_i}}{\vec{V}_{P,i}^{b_i} \cdot \vec{e}_{a,i}^{b_i}}\right)$$

**Nonlinear**:

$$\beta_i^{b_i} = \alpha_{eff,i}^{b_i} - \theta_i$$

$$R_i^{b_i}\tan\left(\beta_i^{b_i}\right) = R_{BV,\#,i}^{b_i}\tan\left(\beta_{BV,\#,i}^{b_i}\right)$$



# Mathematical Formulation IV
# Hub Model

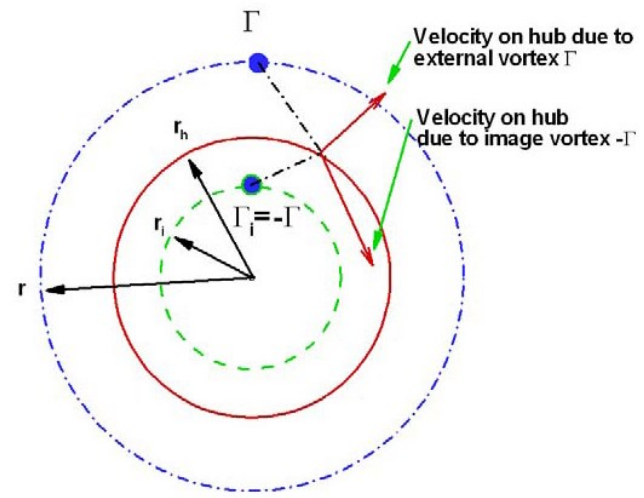
**Hub** Influences Γ;

**Image** vortices;

$$R_{IM,i,b_i} = \frac{R_h^2}{R_{i,b_i}}$$

**Pressure Drag**;

$$D_h = \frac{\rho}{16\pi}\left(\log\frac{R_h}{R_0} + 3\right)(N_B\Gamma_h)^2$$



# Mathematical Formulation V
# Linear Scheme

**No flux** at each **Control Point**;

$$\vec{V}_{P,i}^{b_i} = \vec{V}_{\infty,i}^{b_i} + \vec{V}_{t,i}^{b_i} + \sum_{b_j=1}^{N_B} \sum_{j=1}^{N} \vec{V}_{HS,i,j}^{b_i b_j}$$

$$\vec{\mathrm{u}}_{n,i} \cdot \vec{V}_{P,i}^{b_i} = 0 \rightarrow$$

$$\sum_{b_j=1}^{Z} \sum_{j=1}^{N} \vec{\mathrm{u}}_{n,i} \cdot \vec{V}_{HS,i,j}^{b_i b_j} = -\vec{u}_{ni} \cdot \left(\vec{V}_{\infty,i}^{b_i} + \vec{V}_{t,i}^{b_i}\right)$$

$\mathrm{N} \times Z$ **equations** for $\Gamma_{\mathrm{P}}$;

$$\mathbb{M}_{\mathrm{P}} \Gamma_{\mathrm{P}} = -W_{\infty P}$$

$$\mathbb{M}_{\mathrm{P}} = \begin{bmatrix} \mathrm{M}^{11} & \cdots & \mathrm{M}^{1N_B} \\ \vdots & \mathrm{M}^{b_i b_J} & \vdots \\ \mathrm{M}^{N_B 1} & \cdots & \mathrm{M}^{N_B N_B} \end{bmatrix}$$

$$\Gamma_{\mathrm{P}} = \begin{Bmatrix} \Gamma_1^1 \\ \vdots \\ \Gamma_N^1 \\ \Gamma_1^2 \\ \vdots \\ \Gamma_N^{N_B} \end{Bmatrix}, W_{\infty P} = \begin{Bmatrix} \mathrm{W}_{\infty 1}^1 \\ \vdots \\ \mathrm{W}_{\infty N}^1 \\ \mathrm{W}_{\infty 1}^2 \\ \vdots \\ \mathrm{W}_{\infty N}^{\mathrm{N_B}} \end{Bmatrix}$$

**Hydrodynamic Coefficients**

$$C_{n,pot}^{b_i} = \frac{\rho \Gamma_{\mathrm{i}}^{b_i} \delta l_i \sin\theta_i^{b_i}}{\frac{1}{2} \rho_{V_{P,i}^{b_i}} \delta A_i^{b_i}}$$



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# Mathematical Formulation VI
# Nonlinear Scheme

- CP moves **to adjust** $\frac{\partial C_n}{\partial \alpha} = C_{n_\alpha}$;

$$x_{CPi} = \frac{3}{4}\frac{C_{n_\alpha i}}{2\pi}c_i$$

- $C_{nPot}, \beta_s, \alpha_{eff}$ **updated**;

$$\alpha_{eff i} = \frac{C_{nPot i}}{C_{n_\alpha i}} + \alpha_{L0i}$$

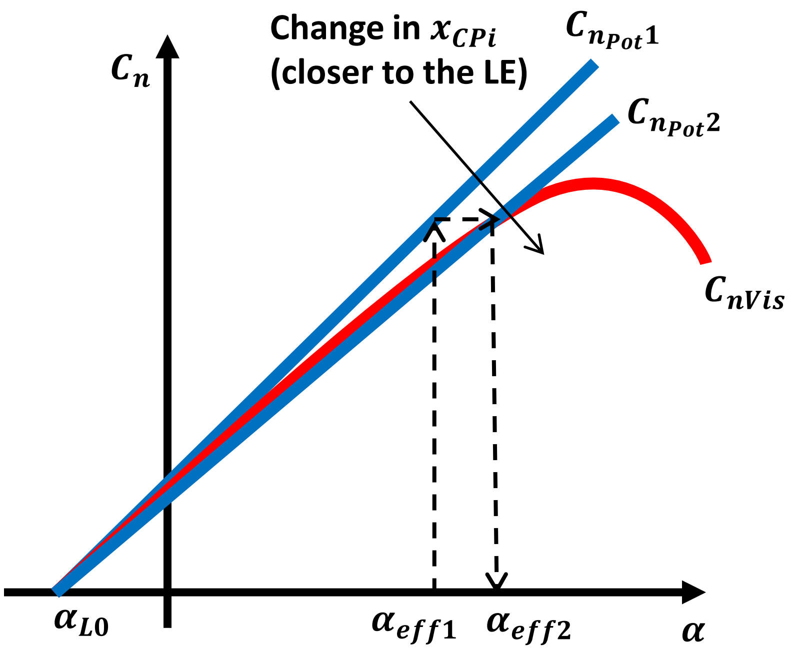
- $C_{n_{Vis}}$ from **2-D data**;

$$C_{n_{Vis} i} = C_{n_{Vis}}(\alpha_{eff i}, Re_i)$$

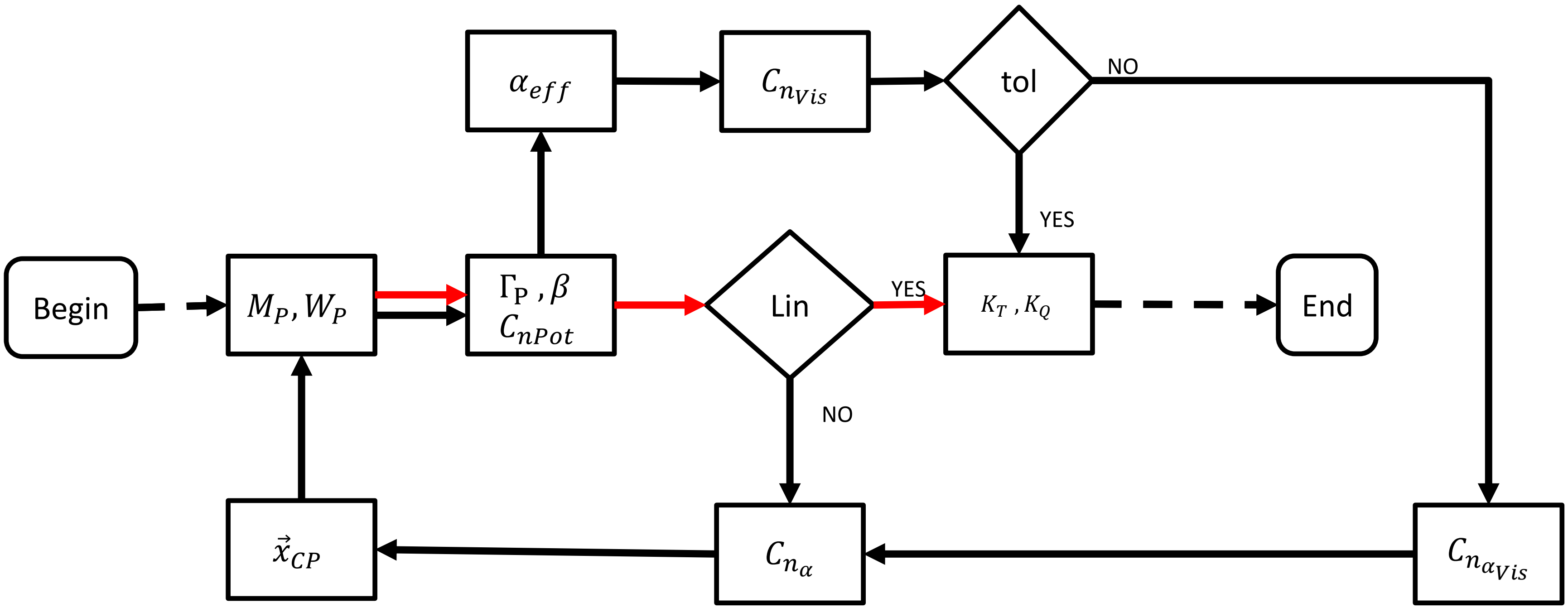
- $C_{n_\alpha}$ **updates**;

$$C_{n_\alpha i} = \frac{C_{n_{Vis} i}}{\alpha_{eff i} - \alpha_{L0i}}$$

$$C_{n_\alpha i} = \Omega C_{n_\alpha i} + (1-\Omega)C_{n_{\alpha_{Vis}} i}$$



# Mathematical Formulation VII
# Flowchart



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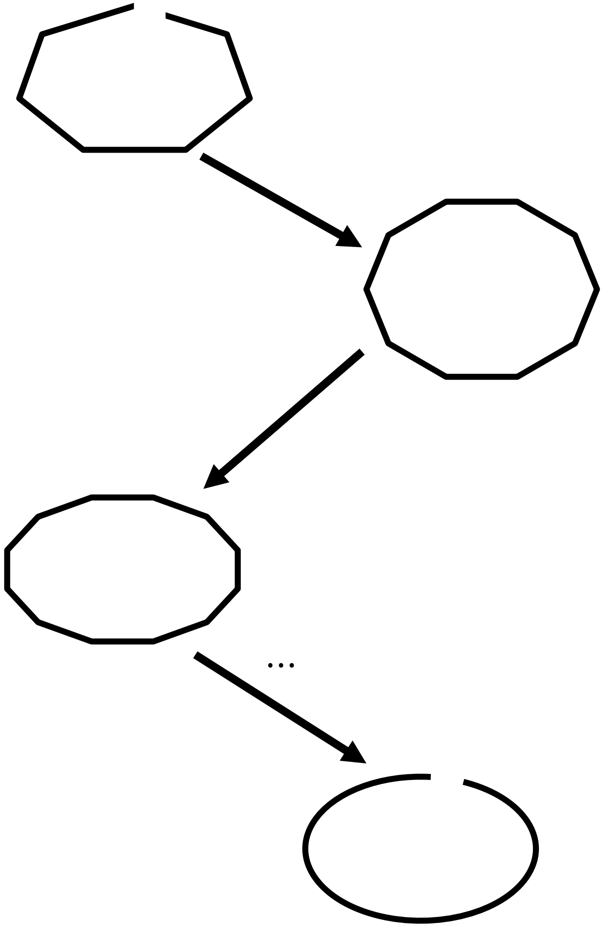
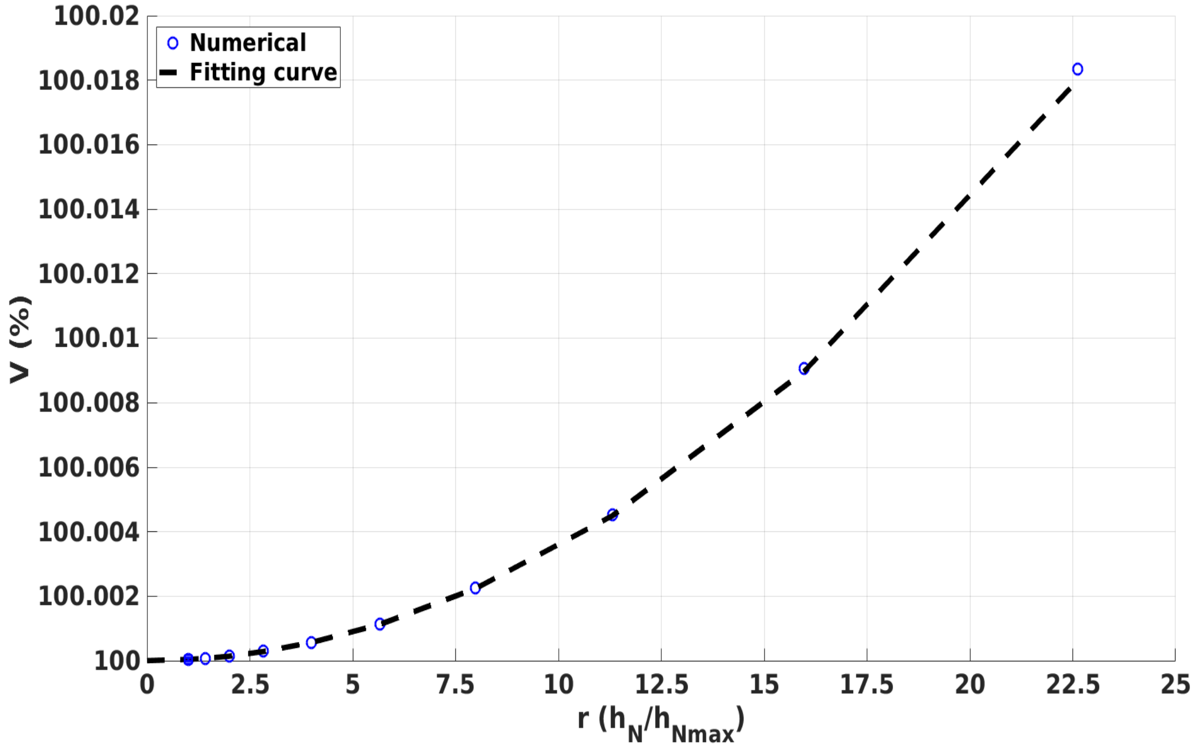
# Results I
# Previous work

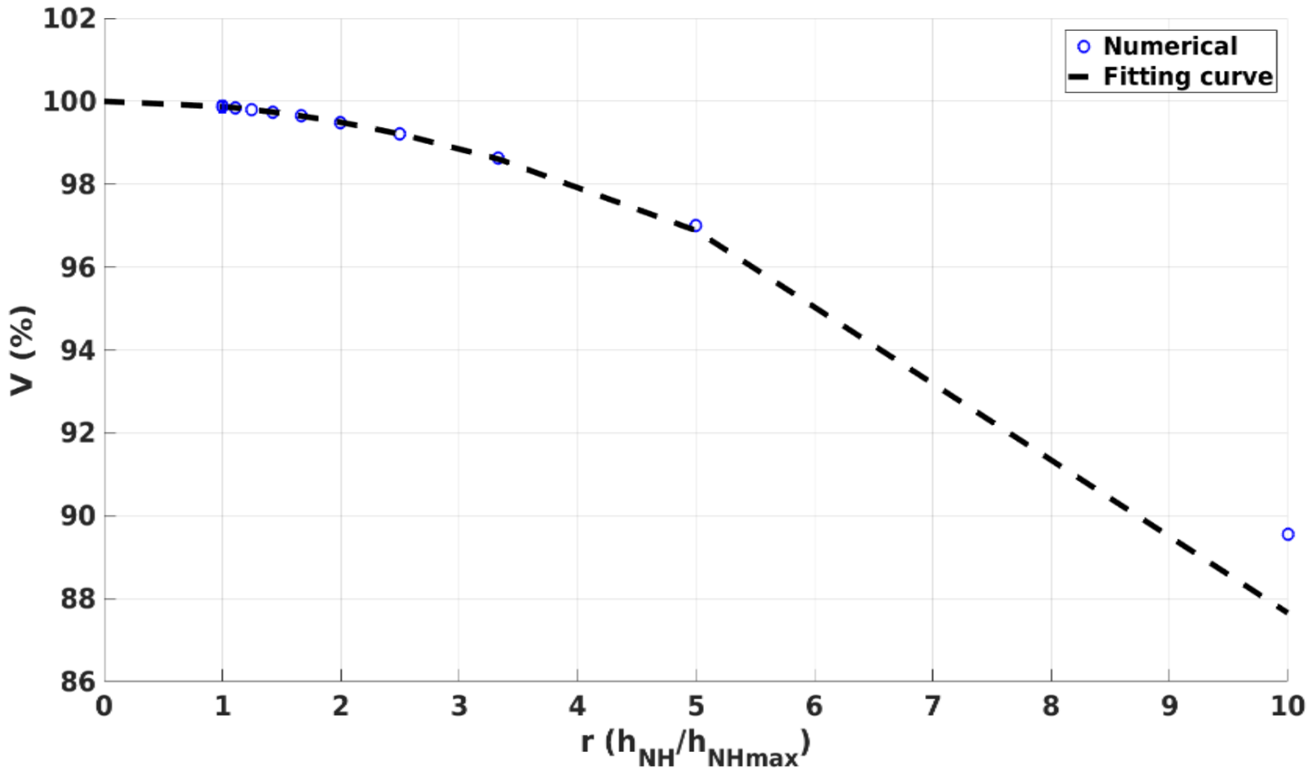


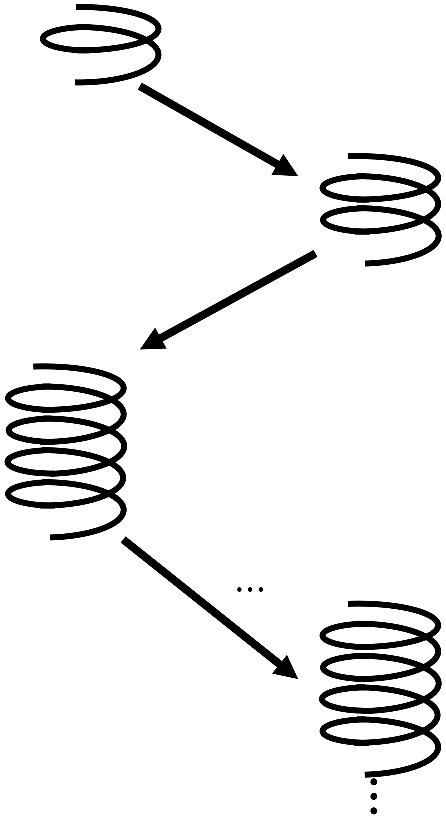

**Convergence** of $V$ – **Single loop** vortex;



# Results II
# Previous work

**Convergence** of $V$ - **number of helices;**



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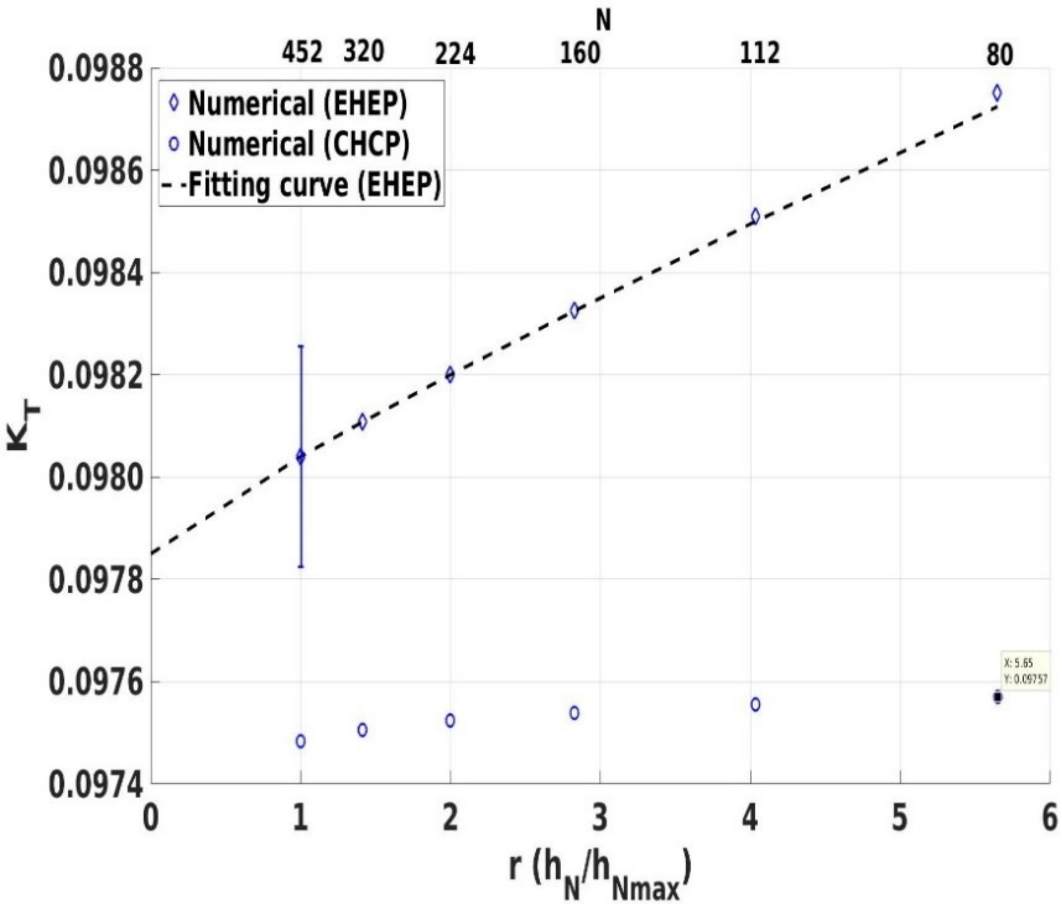
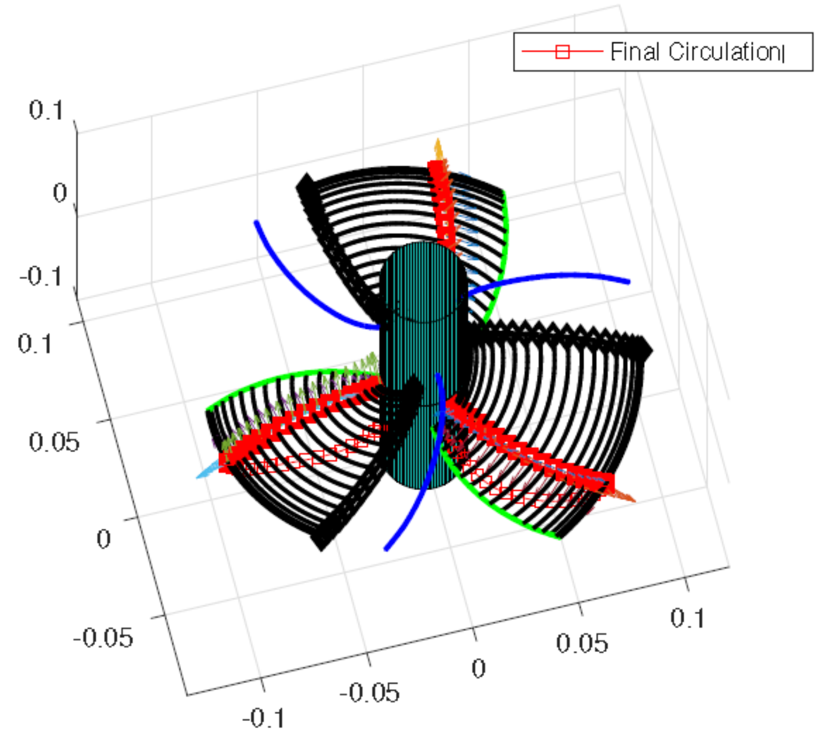
# Results III
# Previous work





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# Results IV
# Current work: Validation

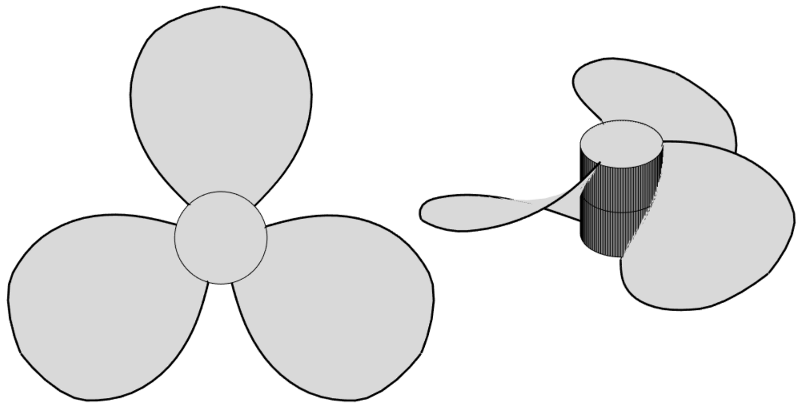
Determine the **accuracy** of the model;

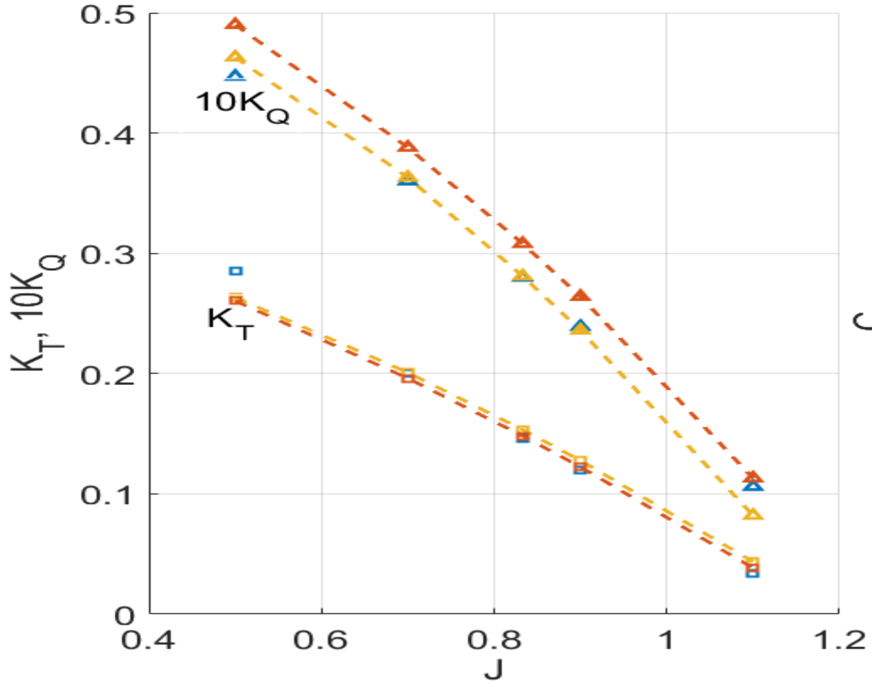
- **After verifications (OMAE 2018)**;

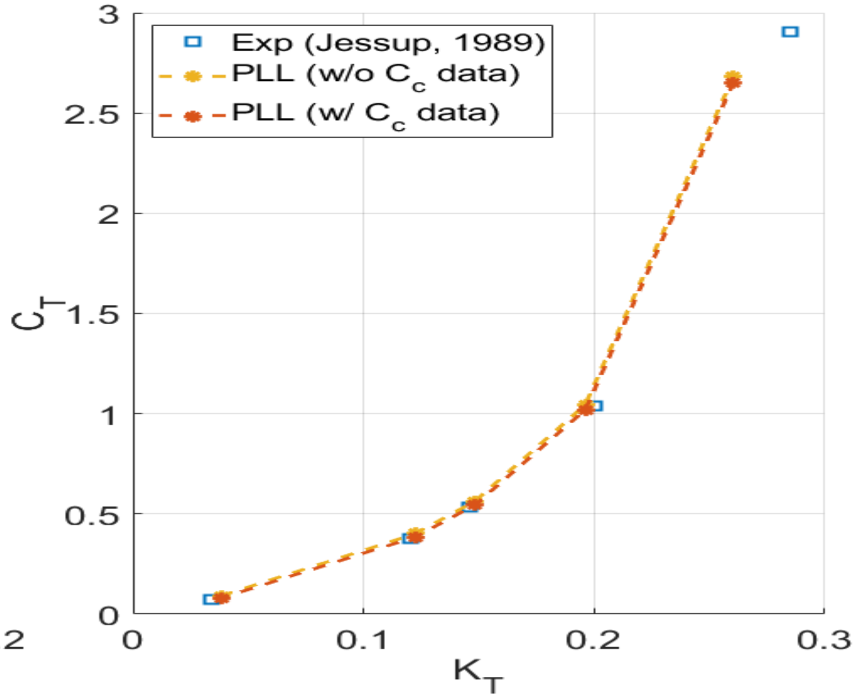
Comparison with **experimental** data;

ASME 2009 **Standard** for Verification and Validation in Computational Fluid Mechanics and Heat Transfer

# Results V – DTMB P4119





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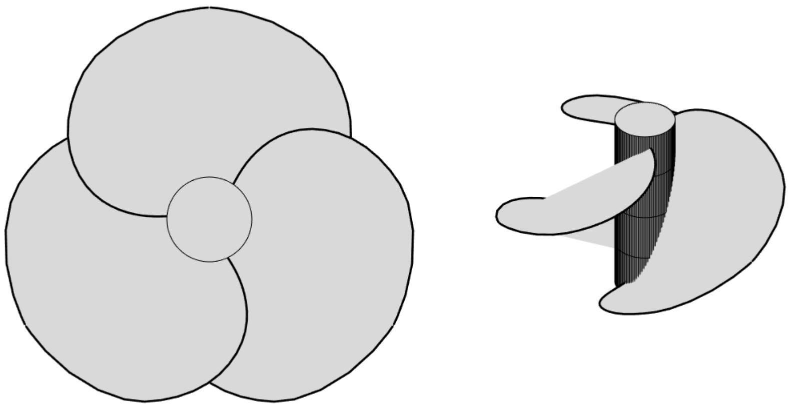
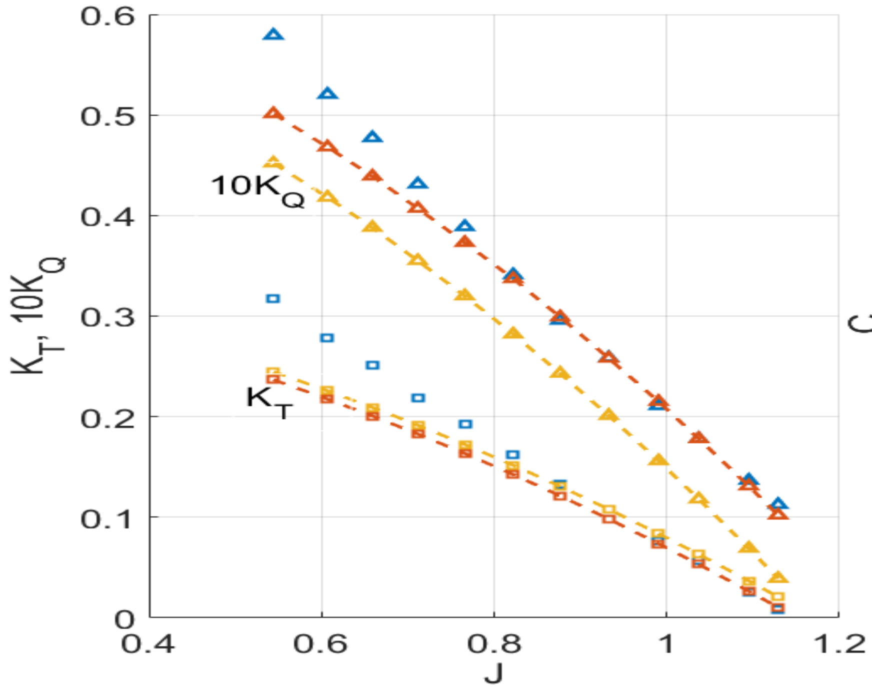
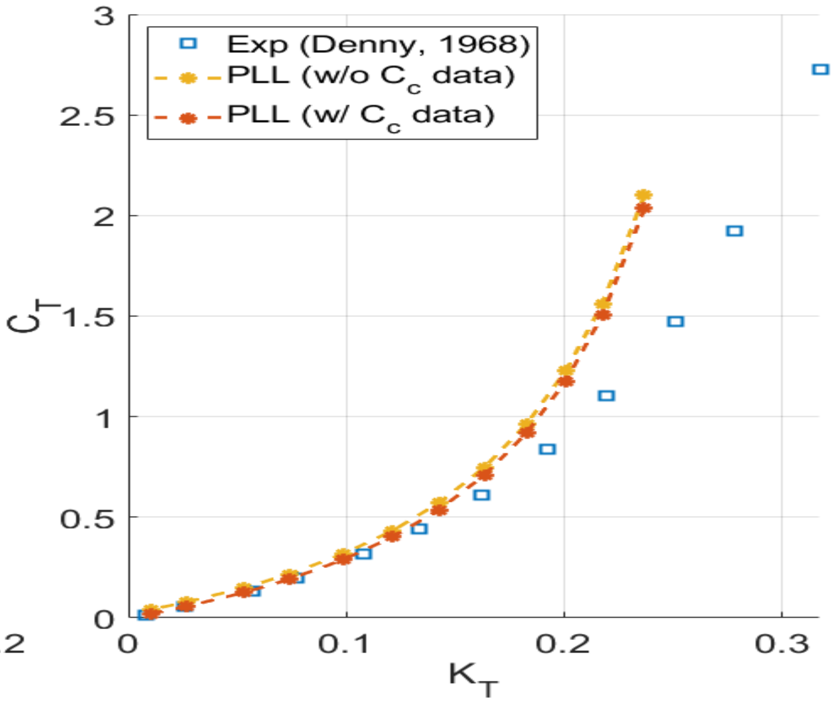
# Results VI – DTMB P4133





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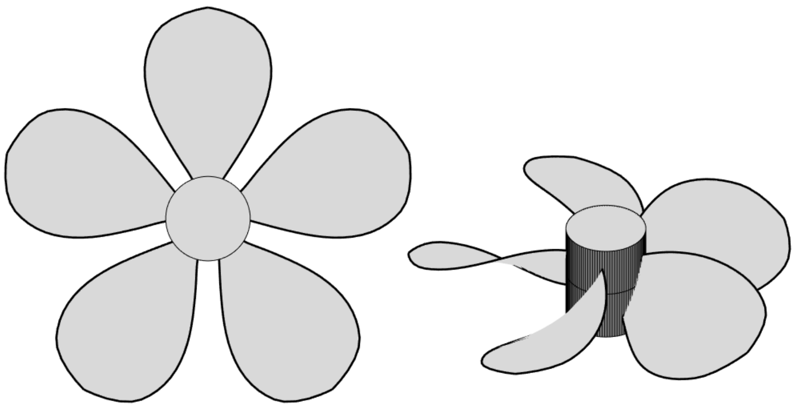
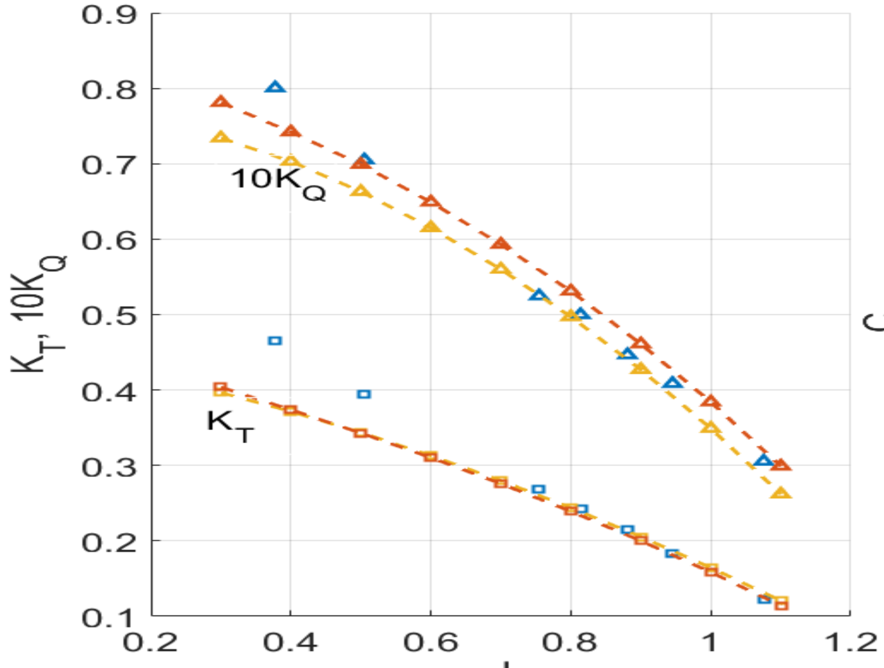
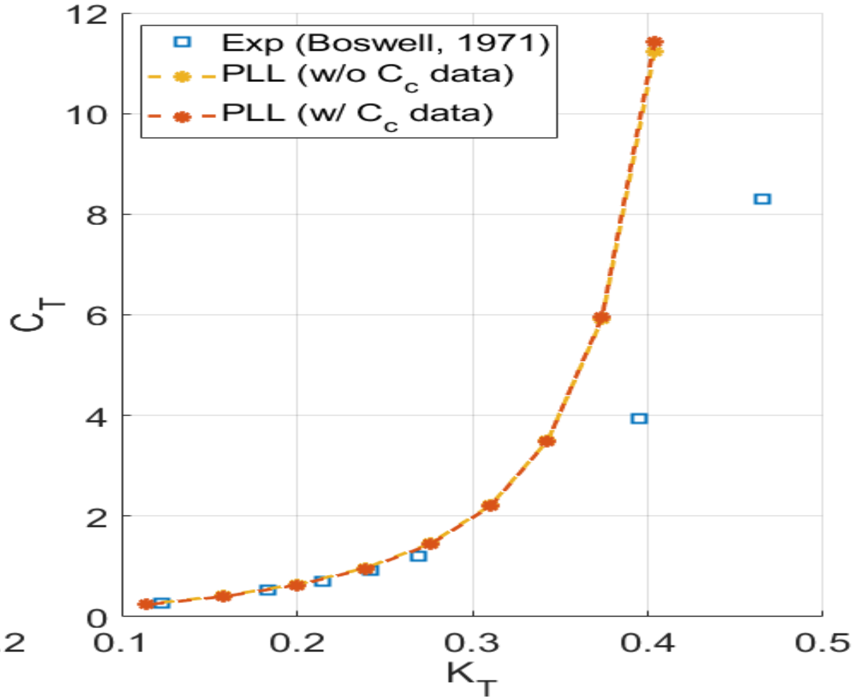
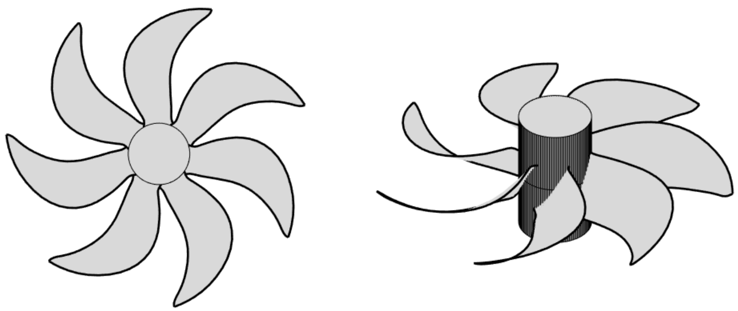
# Results VII – DTMB P4381

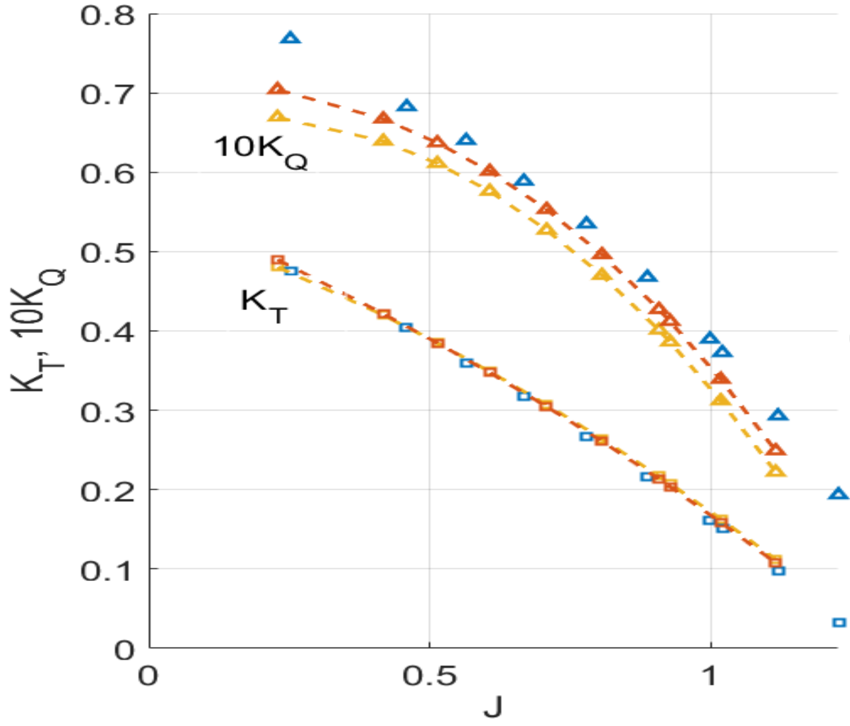


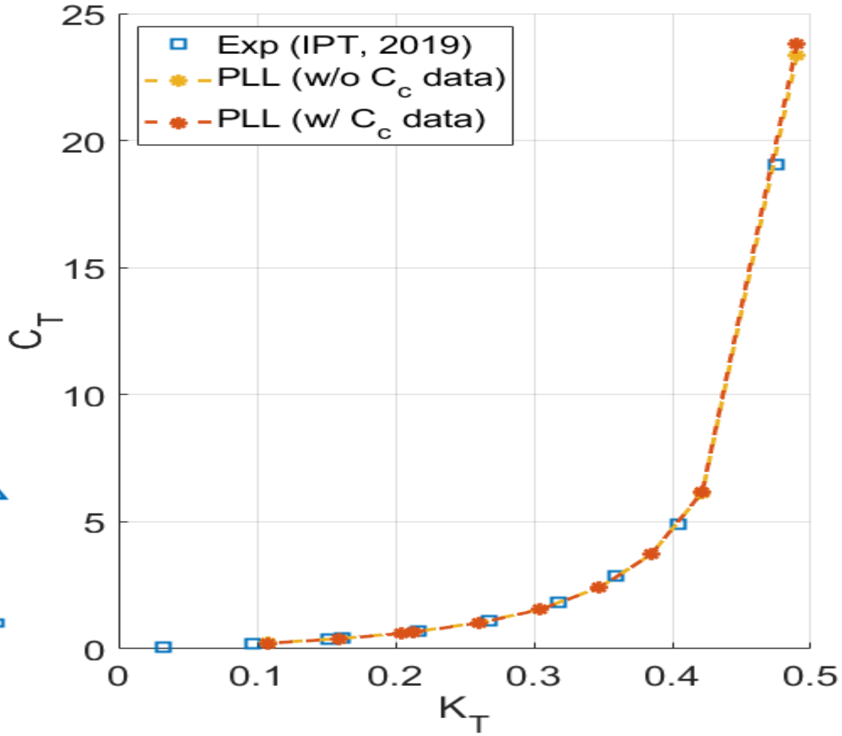


# Results VIII – MOD5 (DARPA)





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# Conclusion

**Novel** propeller LL **formulation**;

+ Strictly imposes **PBC**;
  - general geometries (**rake** and **skew**);
  - **Viscosity** (hydrofoil) and $\beta_w$;

Results;

+ Previous (OMAE 2018): Code and solution verification **showed satisfactory** p;
+ Current: Validation showed **adequate adherence** between numerical and experimental for a series of **geometries** and **range** of **advance coefficients**.



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# THANK YOU

Questions?

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