Computer Based Modeling for Tilt-Wing e-VTOL Propeller Performance

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Abstract

Recent decades have seen a rapid popularization of Urban Air Mobility (UAM) concepts. The new generation of designs presents a wide range of configurations and approaches to exploit the advantages of these vehicles that can be used in civil, commercial, and military applications. One of the more popular concepts is the tandem tilt-wing e-VTOL configuration. However, these types of VTOL configurations bring challenges for performance prediction during crucial parts of flight operations. The flight dynamics during transition regimes where the vehicle transitions from vertical to forward flight and vice versa is not fully understood. In this research, modified blade element momentum theory (BEMT) is used to analyze the blades on NASA's LA-8 testbed prototype tandem tilt-wing UAM. The method proposed finds the important parameters of the propeller performance i.e., thrust, normal force and torque coefficients of the complete propeller system at a range of tilt-angles from 0 to 90 degrees. Results are compared to wind tunnel experiments with the identical propeller, conducted in the ODU Low-speed wind tunnel lab. Surrogate models were created using Gaussian process models to decrease the required computational resources for simulations.

Introduction

Computational flight simulation is a highly valuable tool to analyze the performance and characteristics of an aircraft design in the early stages of prototype design. The primary goal for these types of simulations is to predict the aircraft performance over mission segments and to understand the dynamics of the vehicle before the actual flight testing takes place.

LA-8 is a novel e-VTOL tandem tilt-wing configuration testbed for NASA [1]. It is a reduced scale demonstrator representative of many UAM. The prototype includes 8 motors and propellers (4 CCW and 4 CW), four motor/props per wing. Both the fore and aft wings tilt with motors fixed to the wings. In the wind tunnel, the tilt-wings were tested from zero to 100° incidence angle [1].

Figure 1 LA-8 in NASA 12ft Low Speed wind tunnel [1]

The reduced scale aircraft uses three-bladed propellers with Aeronaut 16 x 8, folding CAM-Carbon blades. An available scan-based, CAD model of the propeller blades was used for analysis. Fourteen equal-spaced cross sections were taken from the propeller blade. Blade airfoils were then analyzed using an XFLR5-based software called JBLADE for coupled viscous/panel method solution of 2D airfoils [2, 3].

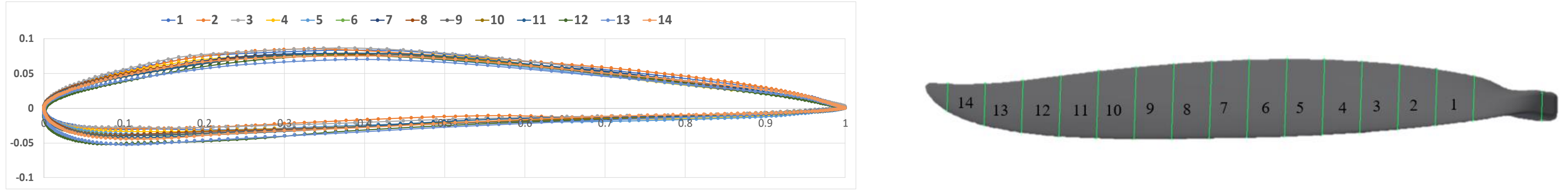


Figure 1 Normalized blade airfoils (left) and Aeronaut 16 x 8 CAM blade CAD scan with cross-sections (right)

Methods of Analysis

Conventionally, blade element analysis does not take in-plane components of the free stream velocity into account. In Figure 4, it's illustrated that this component is defined as $U_Y = U_\infty \sin\alpha_p$. This component acts on the Y_p axis which is the opposite of the normal force of the propeller and the existence of this component makes the flow condition no longer axisymmetric, meaning that the flow is not steady and changes with the azimuthal position [4, 5].

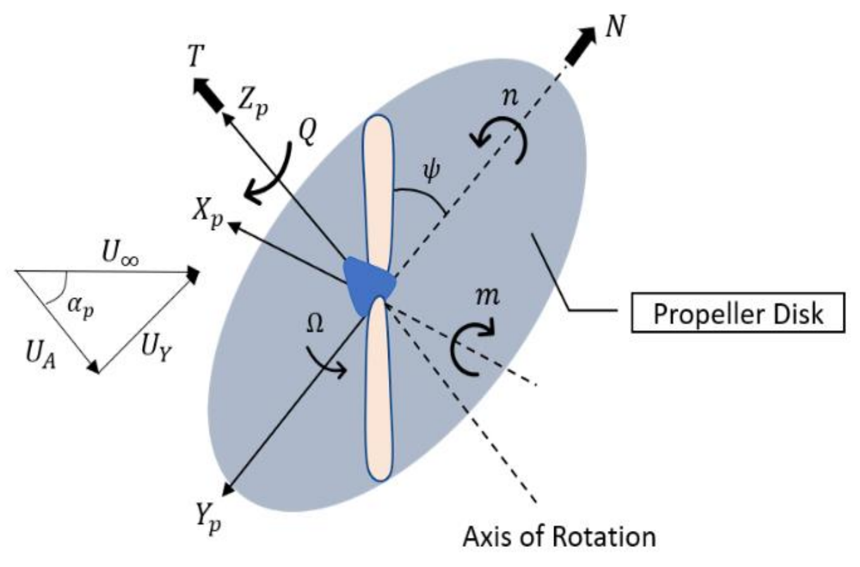


Figure 4 Propeller coordinate system, forces and moments

Methods of Analysis (Cont.)

$$T = \sum_{j=1}^{B} \frac{B}{2\pi} \int_{(j-1)\frac{2\pi}{B}}^{j\frac{2\pi}{B}} \int_0^R \left(\frac{dT}{dr}\right) dr d\psi \qquad N = \sum_{j=1}^{B} \frac{B}{2\pi} \int_{(j-1)\frac{2\pi}{B}}^{j\frac{2\pi}{B}} \int_0^R \left(\frac{dQ/r}{dr} \sin\psi\right) dr d\psi$$

$$Q = \sum_{j=1}^{B} \frac{B}{2\pi} \int_{(j-1)\frac{2\pi}{B}}^{j\frac{2\pi}{B}} \int_0^R \left(\frac{\frac{dQ}{r}}{dr} r\right) dr d\psi \qquad n = \sum_{j=1}^{B} \frac{B}{2\pi} \int_{(j-1)\frac{2\pi}{B}}^{j\frac{2\pi}{B}} \int_0^R \left(\frac{dT}{dr} r \sin\psi\right) dr d\psi$$

Non-dimensional forms for the forces and moments can be achieved from the standard definitions for propeller aerodynamics coefficients for thrust, normal force, and torque.

$$C_T = \frac{T}{B\rho f^2 D^4}, \qquad C_N = \frac{N}{B\rho f^2 D^5}, \qquad C_Q = \frac{Q}{B\rho f^2 D^5}$$

Inflow Algorithm

Inflow angle (ϕ) and the relative wind velocity (W) are calculated using the inflow model [4]. This model solves for both components of the induced velocity (V_A, V_T).

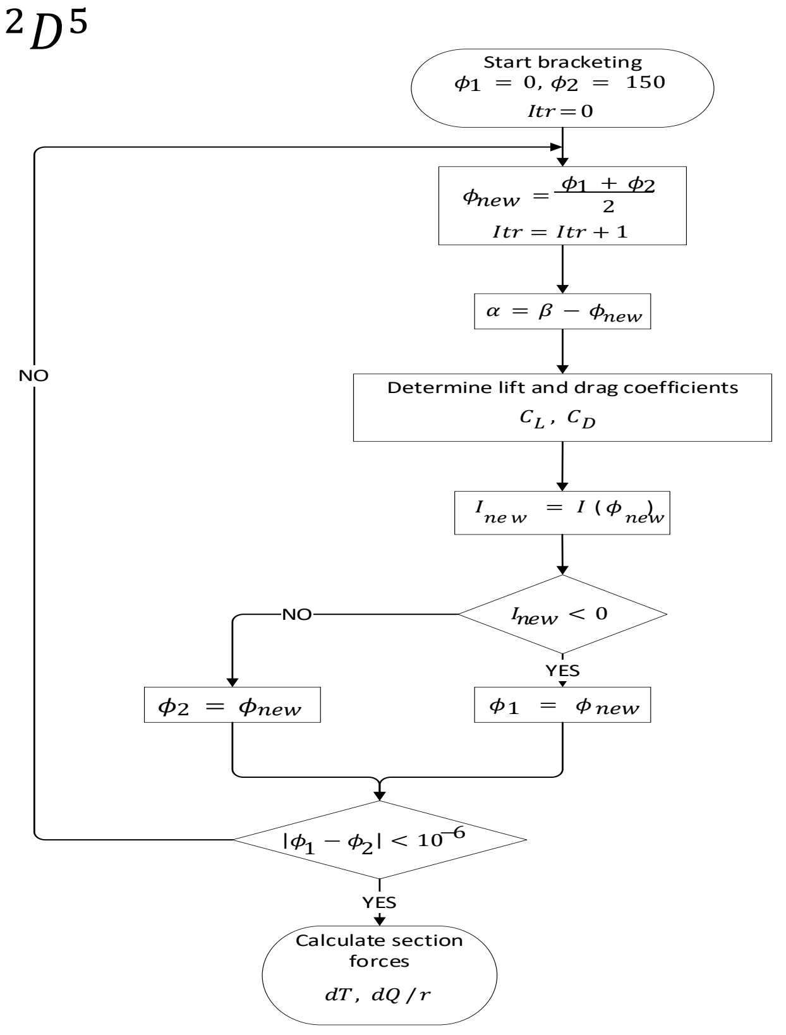
$$\frac{V_A}{W} = \frac{\sigma}{4}(C_L \cos\phi - C_D \sin\phi) \csc\phi, \qquad \frac{V_T}{W} = \frac{\sigma}{4}(C_L \sin\phi + C_D \cos\phi) \csc\phi$$

$$U_A = W sin\phi - V_A$$

$$G(\phi) = \sin\phi - \frac{\sigma}{4}(C_L \cos\phi - C_D \sin\phi) \csc\phi = \frac{U_A}{W}$$

$$H(\phi) = \cos\phi + \frac{\sigma}{4}(C_L \sin\phi + C_D \cos\phi) \csc\phi = \frac{\underbrace{\boxed{\Omega r + U_T}}_{U'_T}}{W}$$

$$\left[U'_T G(\phi^j) - U_A H(\phi^j)\right] \sin\phi^j = I(\phi^j) = 0$$



Start bracketing
$\phi_1 = 0, \phi_2 = 150$
$Itr = 0$

$\phi_{new} = \frac{\phi_1 + \phi_2}{2}$
$Itr = Itr + 1$

$\alpha = \beta - \phi_{new}$

Determine lift and drag coefficients
C_L, C_D

$I_{new} = I(\phi_{new})$

$I_{new} < 0$

NO

YES

$\phi_2 = \phi_{new}$

$\phi_1 = \phi_{new}$

$|\phi_1 - \phi_2| < 10^{-6}$

NO

YES

Calculate section forces
$dT, dQ/r$

Figure 5 Flowchart for solving blade element forces

Surrogate Modelling

Model function of Gaussian Process Model(GPM),

$$y = \underset{\text{Mean}}{\mu} + \underset{\text{Gaussian Process Function}}{z(\boldsymbol{x})}$$

Correlation Matrix,

$$R_{ij}(X,\theta) = exp\left(-\sum_{s=1}^{k=2} \theta_s (x_{is} - x_{js})^2\right)$$

Prediction equation with correlation,

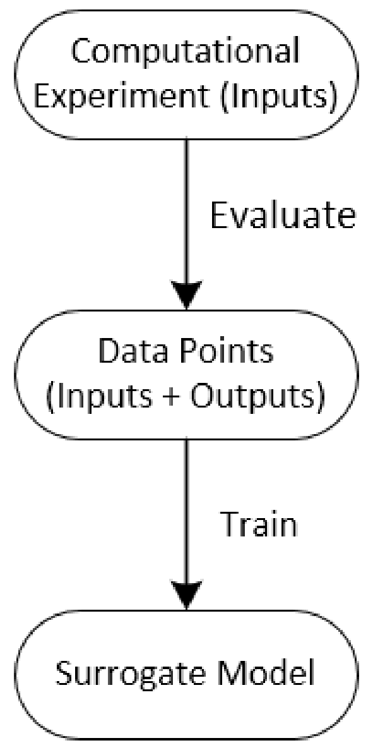
$$\hat{y} = \hat{\mu} + r'(x,\hat{\theta}) R^{-1}(X,\hat{\theta})(y - \hat{\mu}1_n)$$

Maximin design is used for the design space grid generation using the Euclidian distance metric,

$$d(u,v) = \sqrt{\left(\sum_{i=1}^{n} |u_i - v_i|^2\right)}$$

The maximin distance design is then defined,

$$\max_{D} \min_{i,j} d(x, x_i)$$



Computational Experiment (Inputs)

Evaluate

Data Points (Inputs + Outputs)

Train

Surrogate Model

Figure 6 Surrogate (Metamodel) flowchart for computer experiments

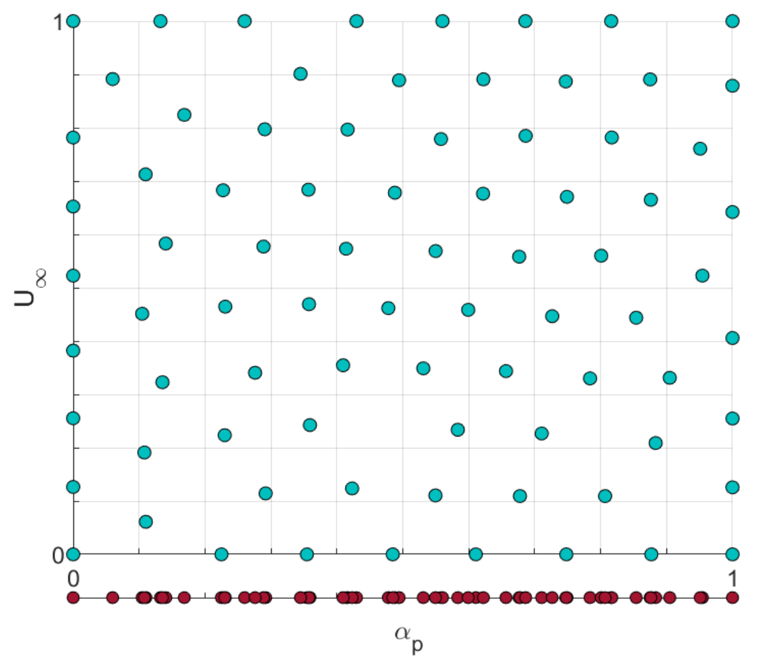


Figure 7 Maximin design for $N_p = 80$

Results

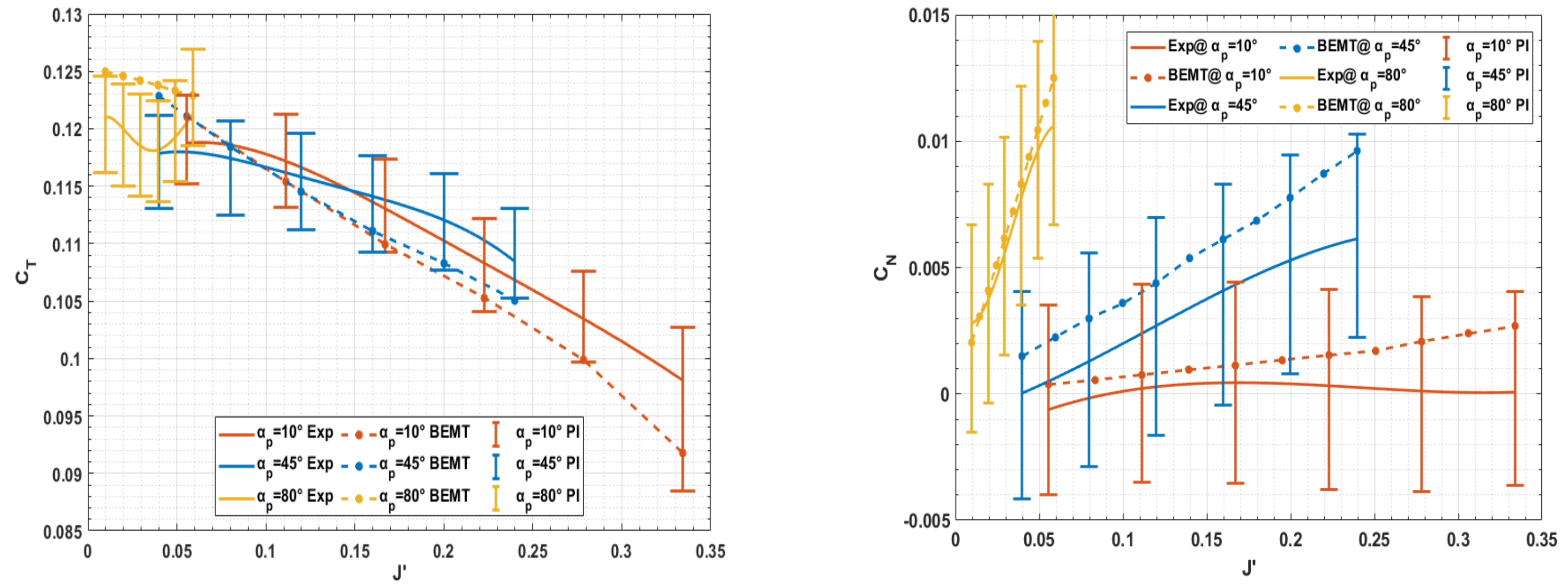


Figure 8 Comparison of thrust and normal force coefficient over J' (effective advance ratio)

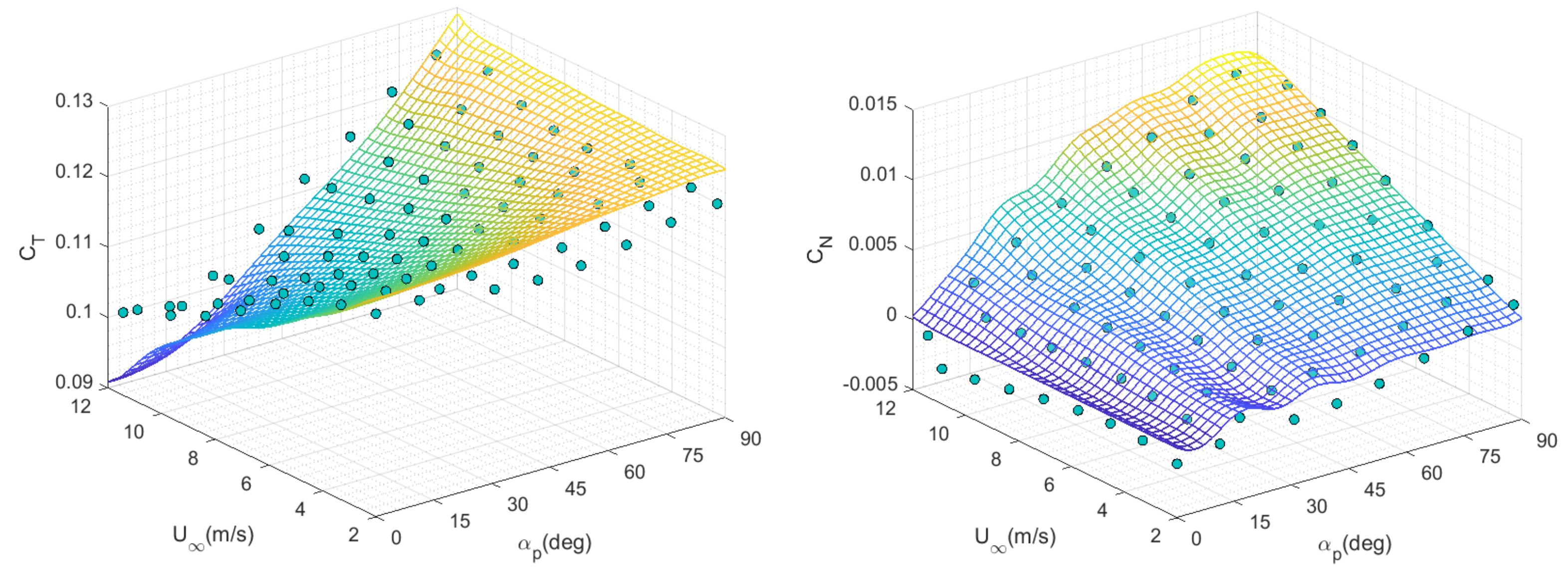


Figure 9 GPR response surfaces compared to experimental regression predictions of [6] for CT and CN (Np=80)

Conclusion

- Baseline BEMT solutions are consistent with the experimental results
    - Current inflow angle provides great accuracy for the thrust coefficient
    - Normal force shows an area of significant disagreement at high velocity and moderate to low incidence angles
        - This is predicted due to the uncorrected wind tunnel boundary effects and noisy experimental data at the wind tunnel.
- Gaussian Process regression(GPR) utilization allows real-time propulsion calculations for use in flight dynamics simulations
    - Maximin space filling designs coupled with the Gaussian Process Regression.
    - Error analysis using the GPR versus the experiment
        - Maximum error for thrust coefficient stays under 10%

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