Machine-Learning Strategies for Aircraft Efficiency Enhancement with Unsteady Inflow Conditions

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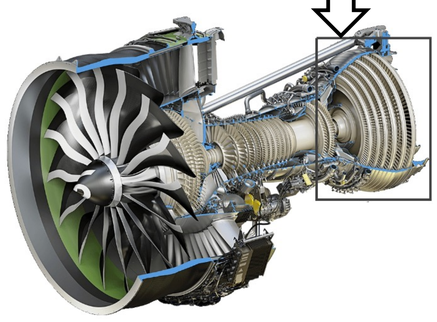
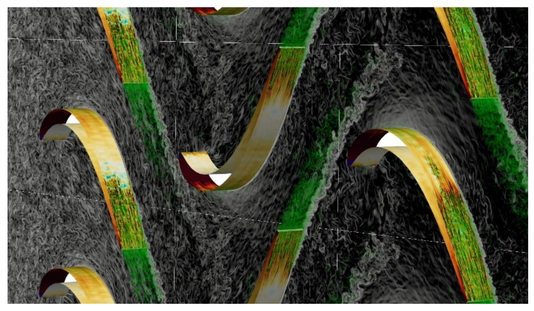
Background

Commercial aviation burns over **360 billion liters of fuel** every year!



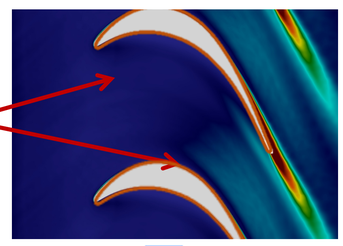


Unsteady flow leads to **higher loss and efficiency reduction!**

Motivation:

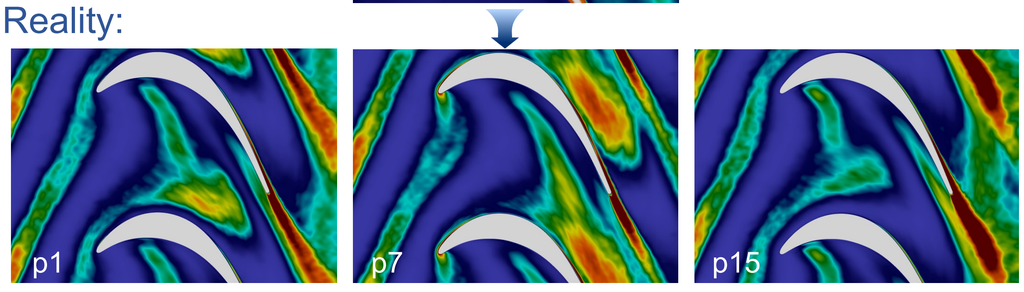
Time averaging data:

Missed wake distortion and impingement



Unsteady physics is averaged out !

Reality:



How can machine learning learn and retain unsteady flow information?

Novel ML Extension for Unsteady Inflow case

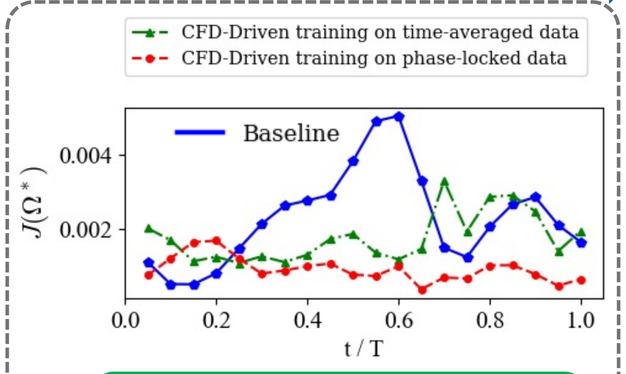
Model Correction

Gene Expression Programming

Unsteady RANS

Model Evaluation

$J_{MOI}(|Q_{Truth} - Q_{URANS}|)$



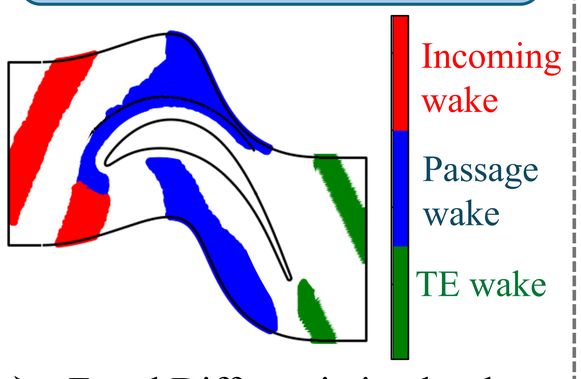
Phase-lock averaged

$Q^*: J(\Omega^*)/J(\tau_w{}^*)$

- Transient information

Turbulence model:

$g_n(I_1, I_2, \boldsymbol{N_1}, \boldsymbol{N_2}) \Rightarrow \Omega^*$



- Zonal Differentiation by the various input features $\boldsymbol{N_1}, \boldsymbol{N_2}$

Transition model:

$\boldsymbol{c_{ss}}(f_{pg}, S/\Omega) \Rightarrow \tau_w{}^*$

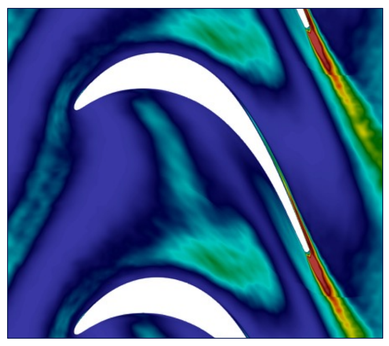
- shear-sheltering function:
  $f_{SS} = \exp(-(c_{SS}\Omega y/k)^2)$
- large-scale turbulent fluctuation contributes to LKE production:

$$k_{T,l} = (1 - f_{SS})k,\ \gamma = \frac{k_{T,s}}{k_l + k_{T,s}}$$

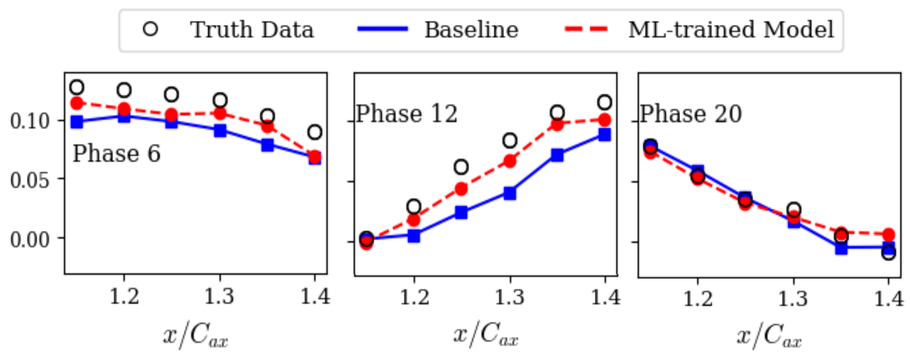
- $\boldsymbol{c_{ss}}$ contains information of incoming wake disturbances

Model Training

I: Turbulent Model Development

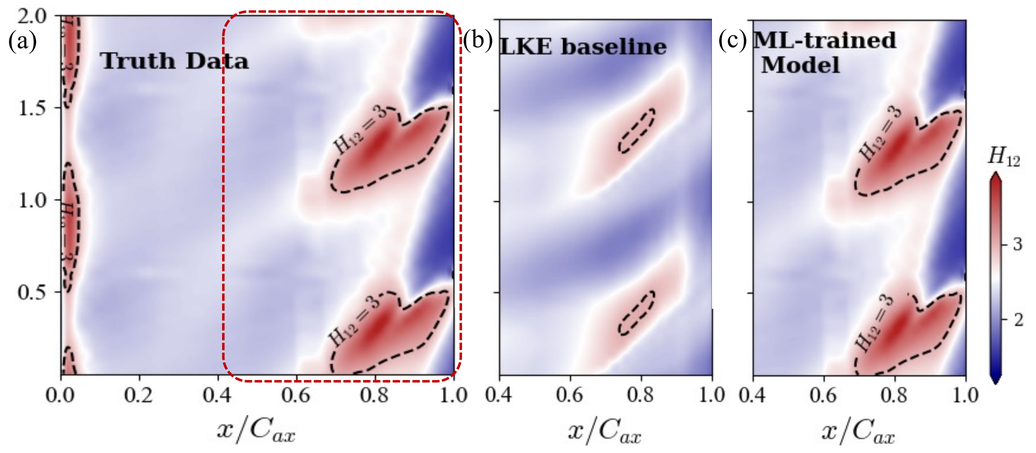


Flow Configuration of Training Case (one moving bar)



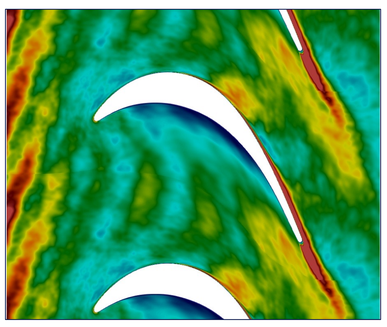
Wake Mixing Downstream of Training Edge

II: Transition Model Development

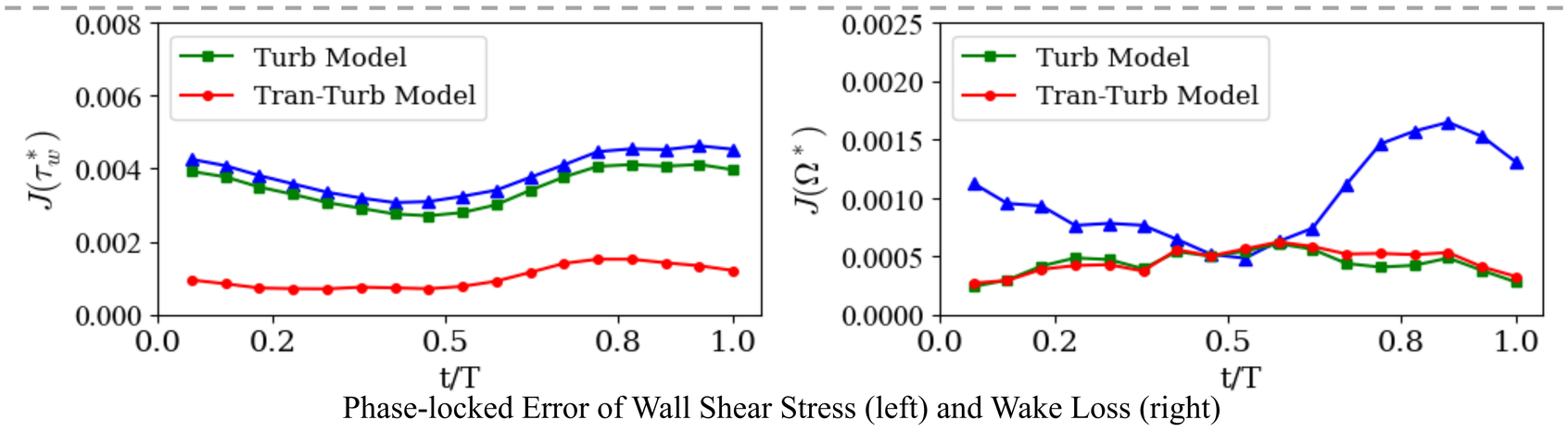


Space-Time Diagram of Shape Factor

Model Testing



Flow Configuration of Testing Case (two moving bars)



Phase-locked Error of Wall Shear Stress (left) and Wake Loss (right)

Conclusion

- The ML-trained models significantly **improved predictive accuracy**, reducing errors to roughly **20%** of the baseline.
- These improvements **generalize well across** a range of incoming wake dynamics.

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Funding: Melbourne Graduate Scholarship