Development of Physics-Based Transition Models for Unstructured-Mesh CFD Codes Using Deep Learning Models

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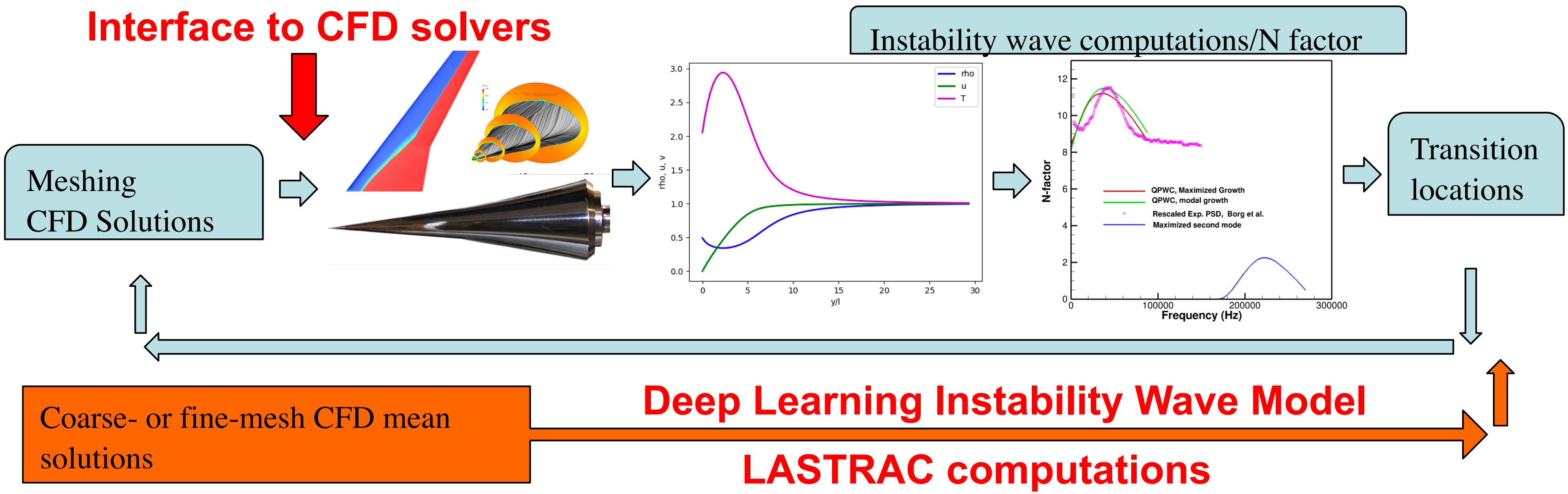
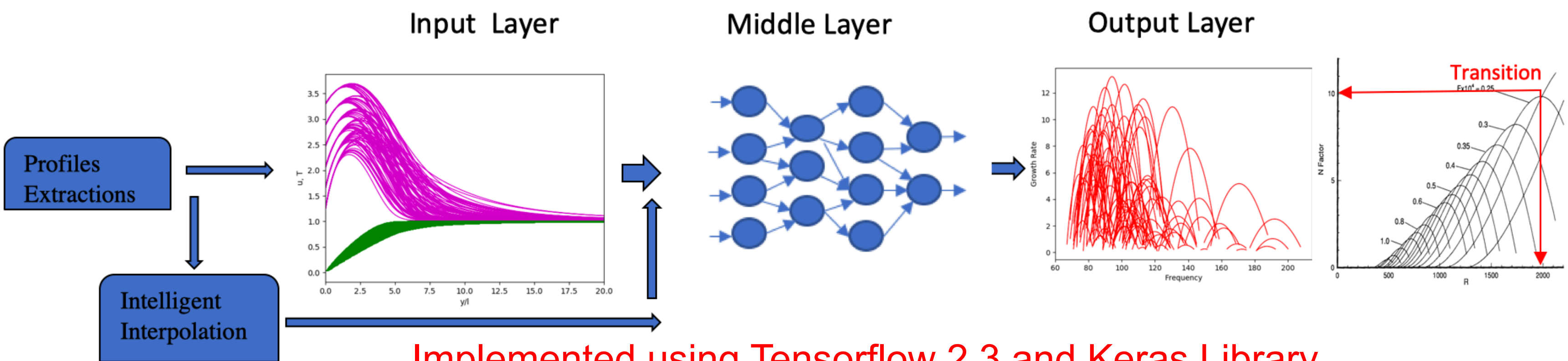
Physics-Based Transition Prediction Paradigm



- CFD solver provides either a converged laminar or instantaneous transitional solution
  - Mean flow profiles extracted
  - Instability wave evolution solved along the surface
  - N-factor integration over the surface gives transition onsets
- Stability computations carried out in one of two ways
  - Deep learning instability model in lieu of table lookup
  - Direct LASTRAC computations
- Interface to CFD solvers development

Deep Learning Model for Instability Wave Prediction

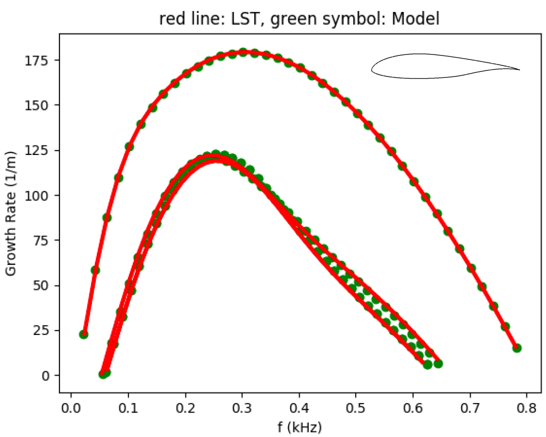


Implemented using Tensorflow 2.3 and Keras Library

- Input Layer
  - Normalized flow profiles with respect to boundary-layer similarity scale and freestream conditions
    - To reduce training set size and increase robustness of predictions
  - Flattened vector inputs $[\mathrm{y},\ \rho,\ u,\ v,\ w,\ T,\ Re_x, \dfrac{dp}{dx},\ M_\infty\ldots]$ to the deep learning model
- Middle Layer
  - 5 or 6 fully connected layers with ELU or SELU activation functions
- Output Layer
  - Predicted instability wave spectrum $[f,\ -\alpha_i]$ for the input profile
- Training data precalculated using LASTRAC for selected meanflows
  - Boundary-layer code for flat plates, sharp cones, 2D airfoils and infinite swept wings
  - NASA’s VULCAN-CFD Navier-Stokes codes for blunt cones
  - Mach number ranges from 0 to 7, thermal conditions from $T_w/T_{adw} = 0.2 - 1.6$
  - Covers TS, first- and second-mode, and crossflow instability

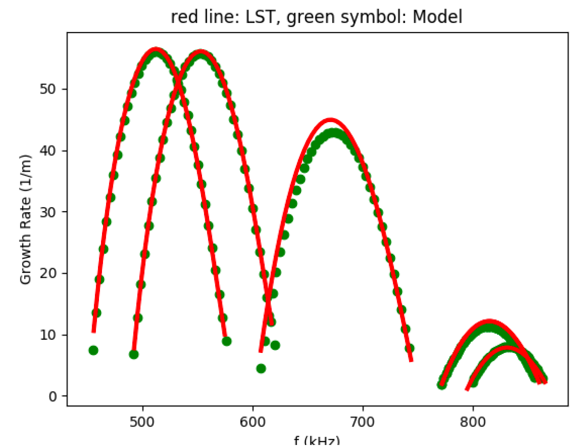
Developed Instability Model Predictions for Various Instability Mechanisms

- Model predictions compared against LASTRAC linear stability theory (LST) solutions

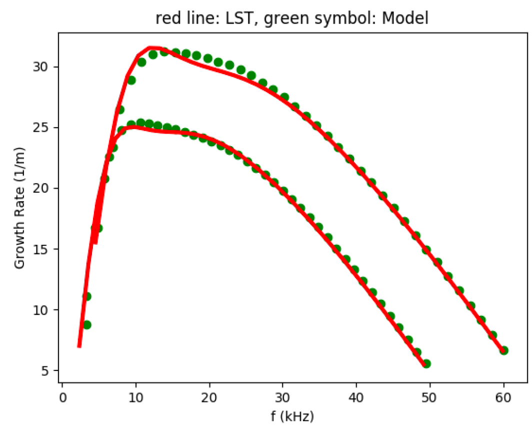


TS wave: incompressible flow over a 2D wing

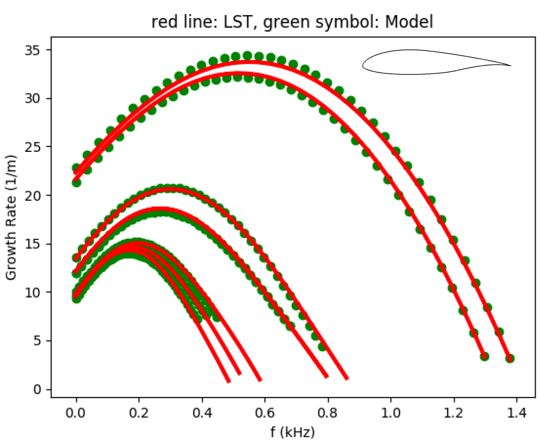
Lines: LST solutions
Symbols: Model predictions



Second-mode instability : Mach 5 over 7° blunt cone

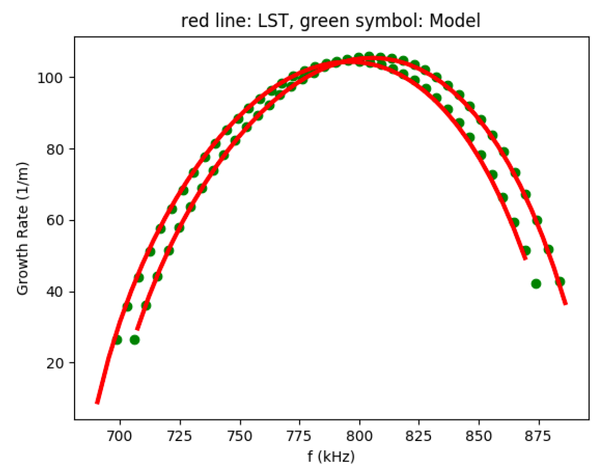


Optimized first-mode instability : Mach 2 flat plate



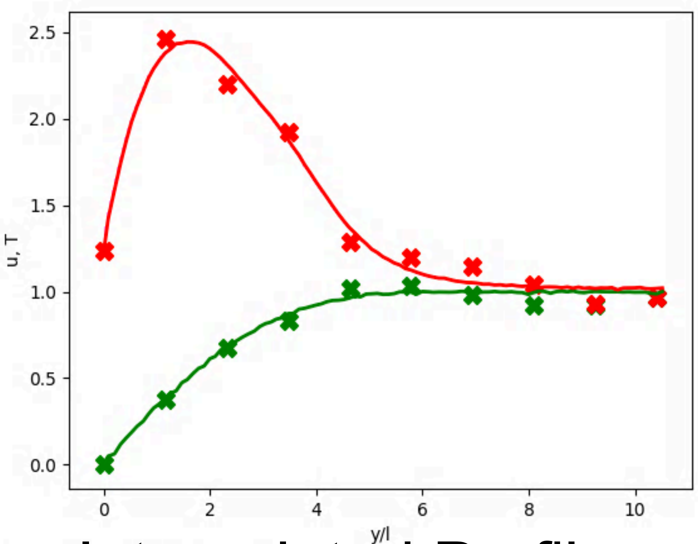
Optimized cross flow instability : 45° swept wing

Showing disturbance growth rates vs frequency for various transition mechanisms



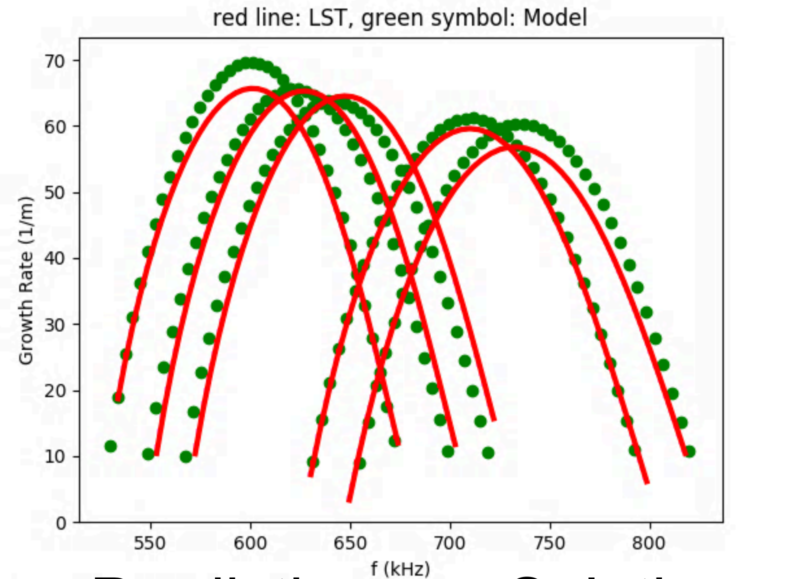
Second-mode instability : Mach 6 over 7° sharp cone

A Deep Learning Model for Intelligent Profile Interpolation

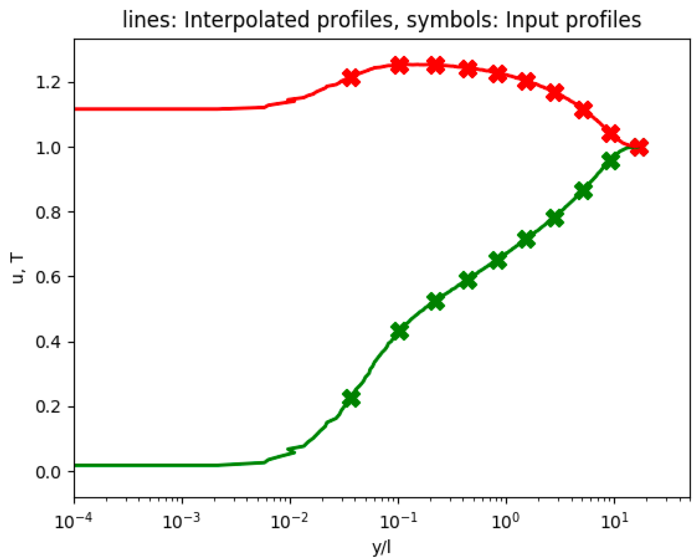


Interpolated Profiles

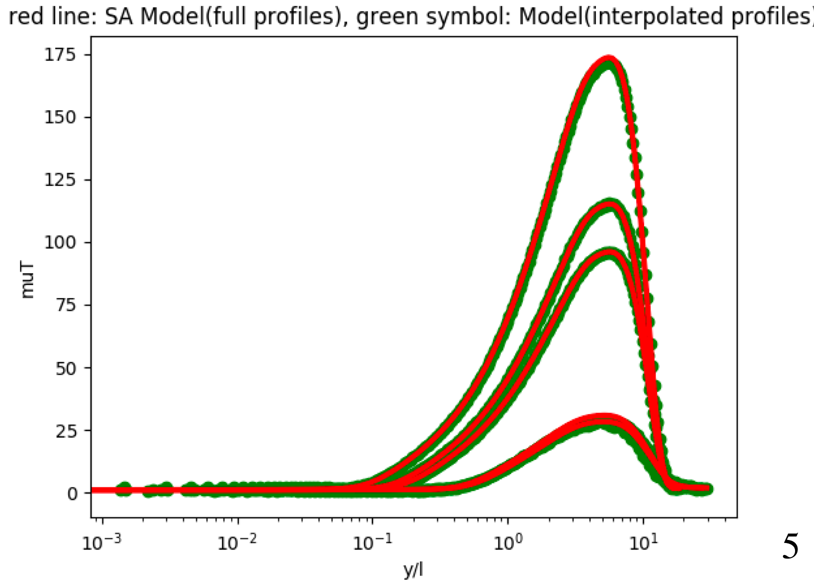
Mach 6 blunt cone second mode



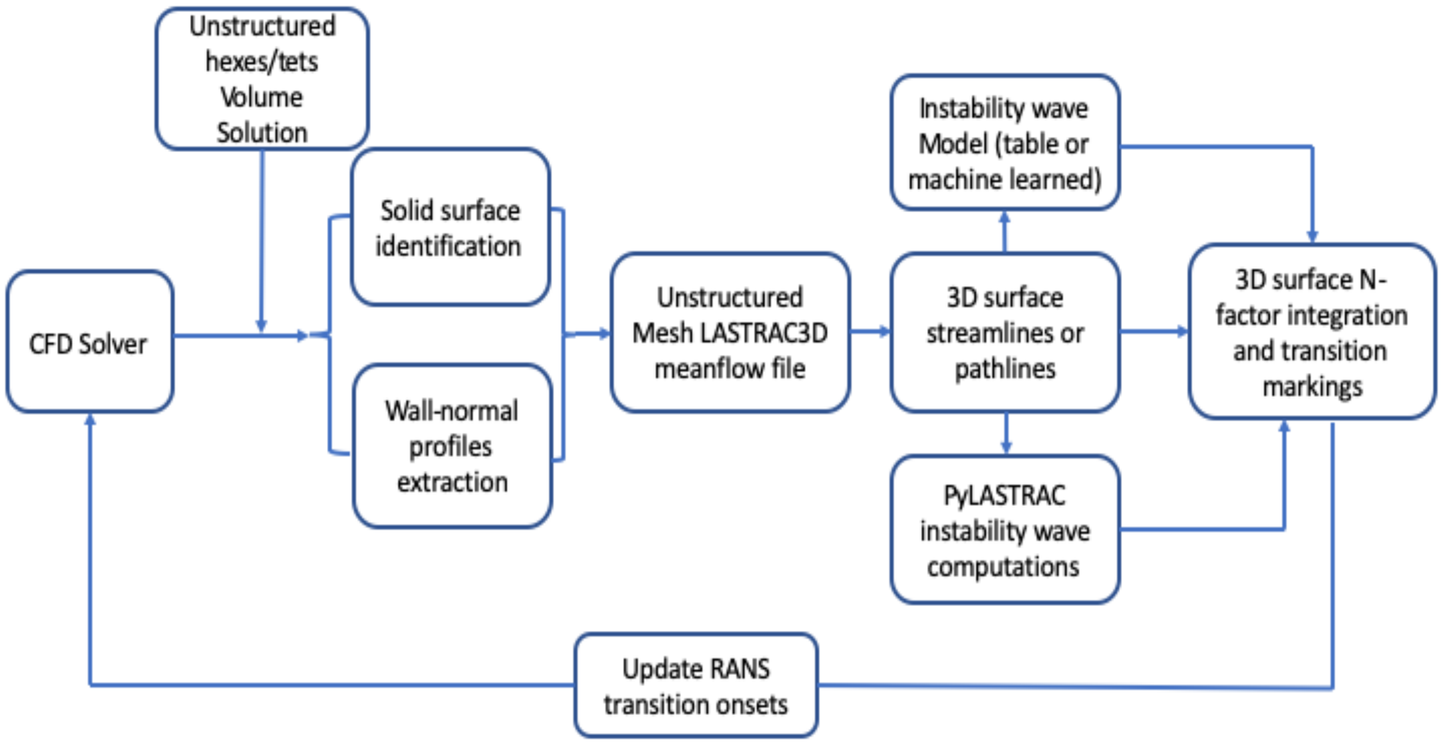
Predictions vs Solutions



Mach 2 Turbulent flat plate



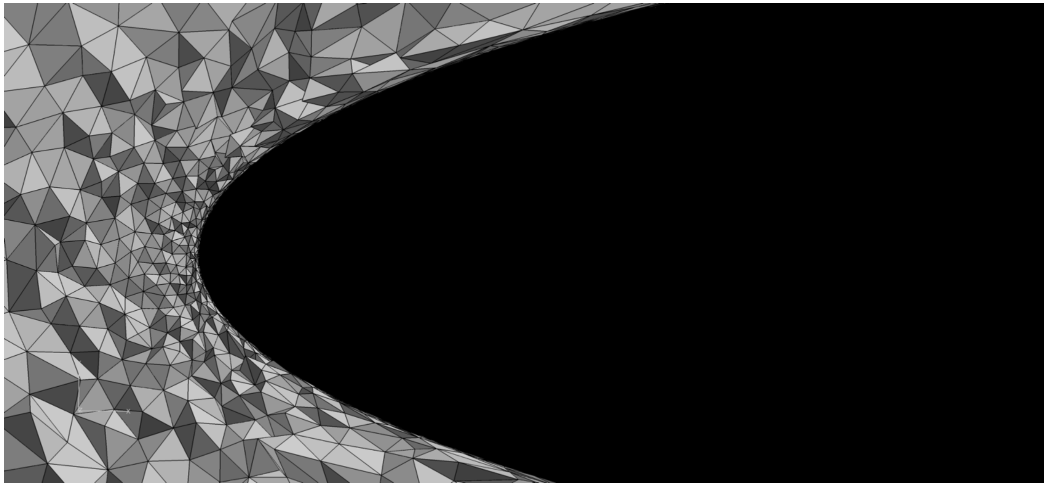
Interface to CFD Solvers

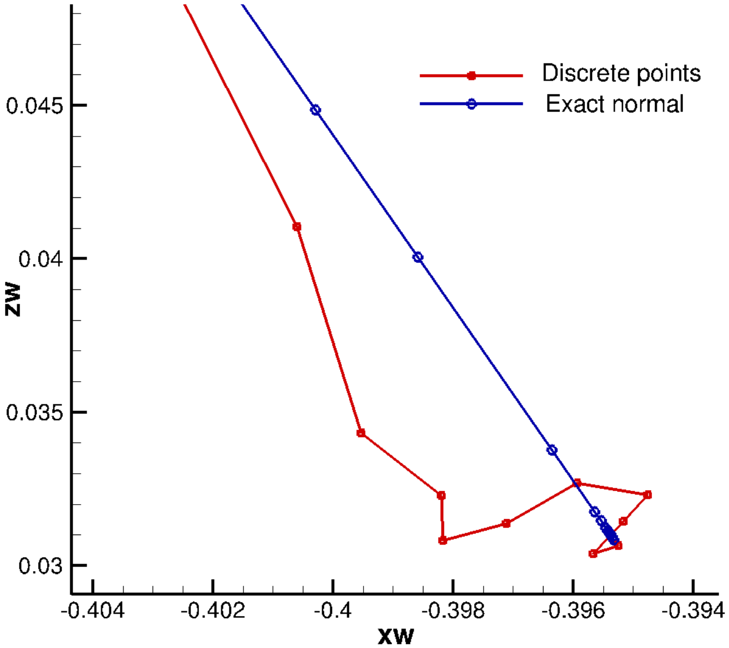


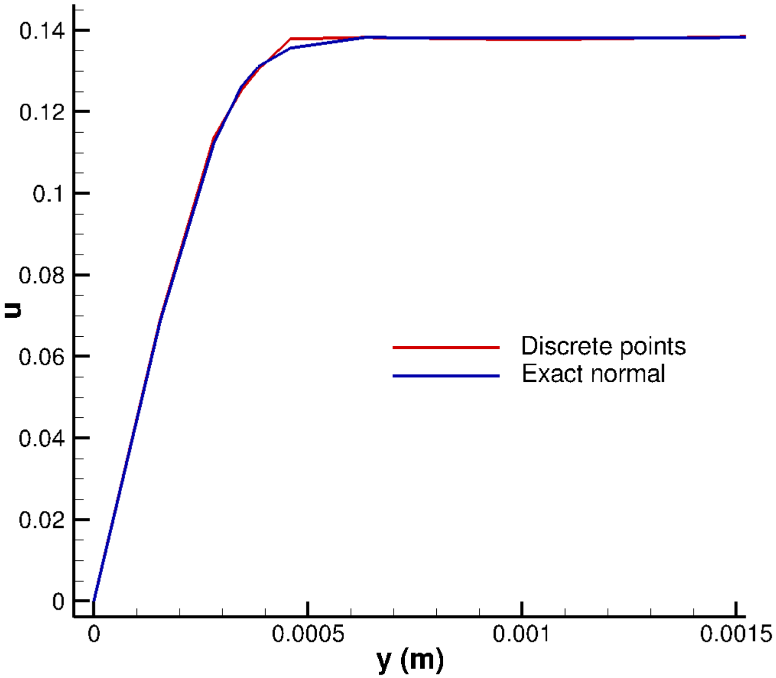
- Input is a generic unstructured-mesh volume solution data structure
- Viscous surface and wall-normal profile extraction tools
- Unstructured-Mesh LASTRAC Implementations
- N-factor integration over arbitrary 3D surfaces
- Interface software integration
  - Goal is to provide a minimal user-input or hands-free transition model package

Wall-normal Profile Extraction

- Use two approaches
  - Closest vertex
  - Exact wall-normal points

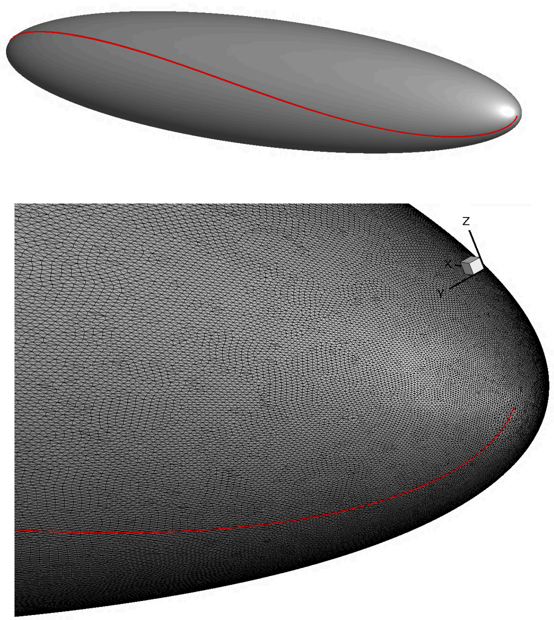


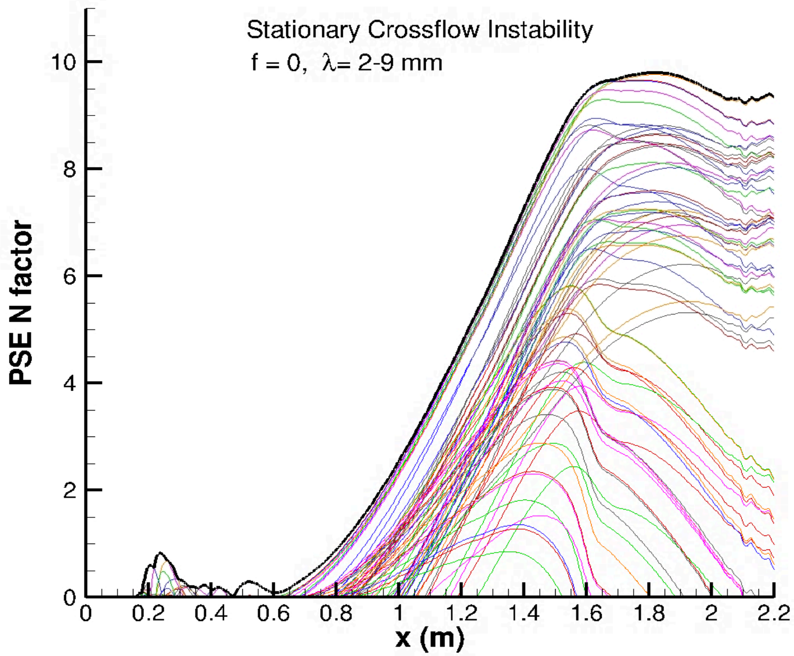




LASTRAC Unstructured Mesh Meanflow

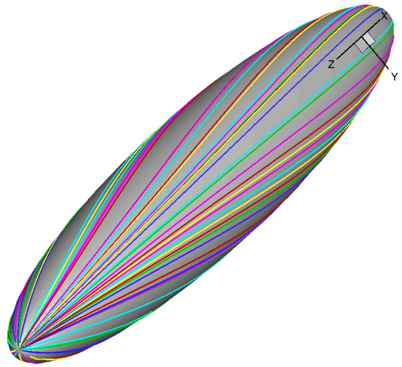
- New implementation to be added to LASTRAC 3.0 formal release
  - Allows either unstructured surface triangular or quadrilateral meshes
  - Wall-normal velocity profiles in Cartesian coordinates
  - Unstructured CFD solver can output meanflows for LASTRAC directly if wall-normal profiles extraction tool is available within the code

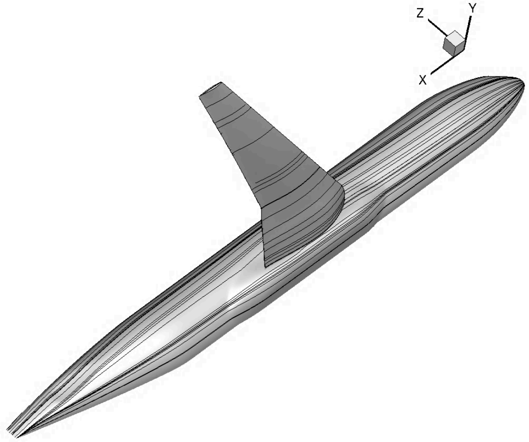




Transition Prediction with Unstructured-Mesh LASTRAC

- N-factor integration along selected paths
  - Streamlines over the entire surface (most popular)
  - Vortex or group-velocity lines for crossflow instability
  - User-supplied path lines
  - Using either LST or linear PSE
- PyLASTRAC
  - A set of front-end Python tools wrapping most LASTRAC functionalities in a much more user friendly fashion
  - Compute streamlines and identify instability waves and perform N-factor integrations autonomously over the entire surface
  - Using computed N factor and user-supplied transition criteria, output markings of transitional state on all surface vertices

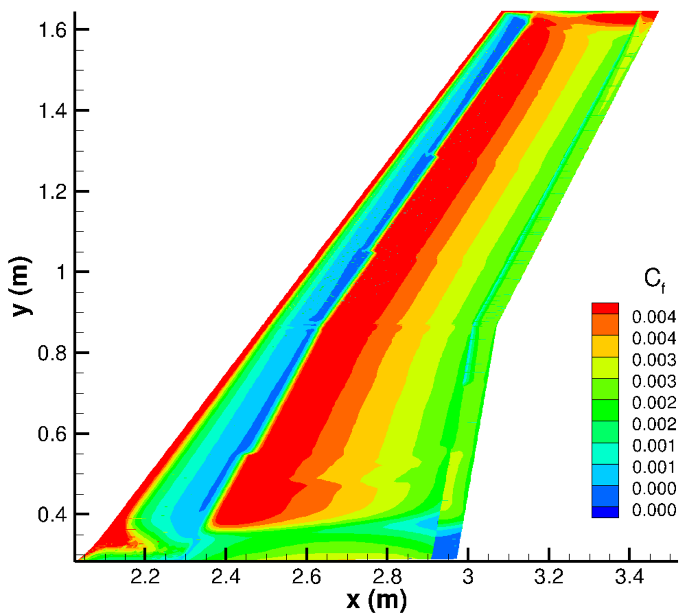




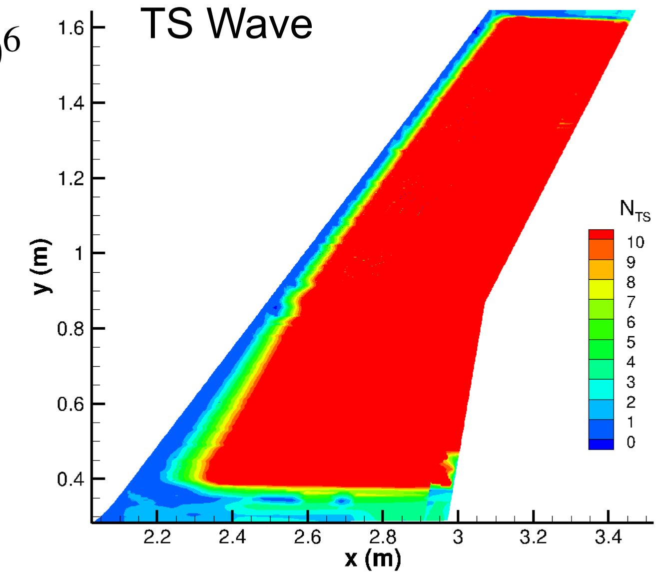
NASA Juncture Flow Experiment Transition Prediction (Linear PSE)

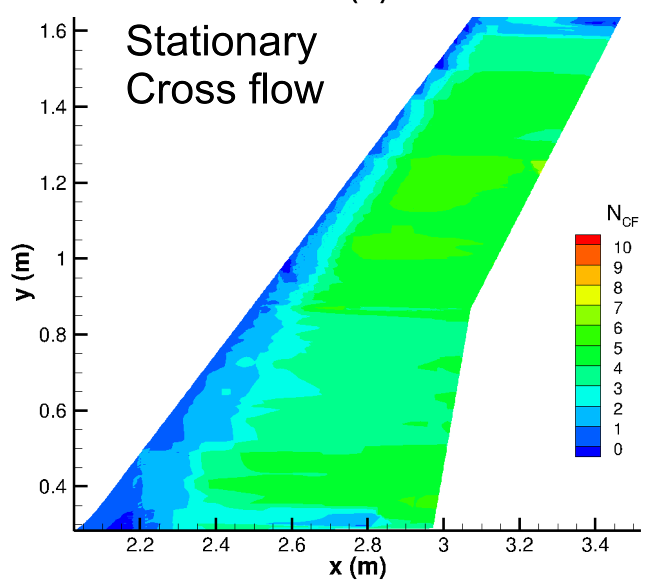
- OVERFLOW RANS solution
- Upper (suction) surface, AOA $5°$, Re = 2.4×10^6

RANS solution by pushing back transition



Friction Coefficient

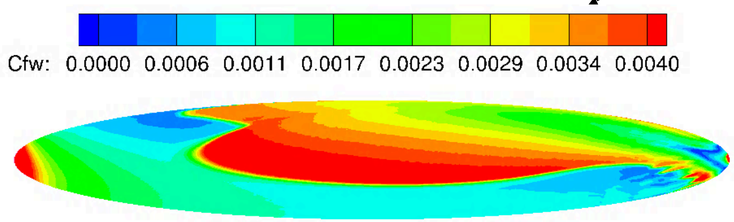


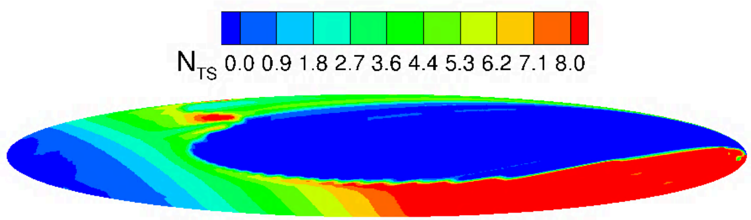


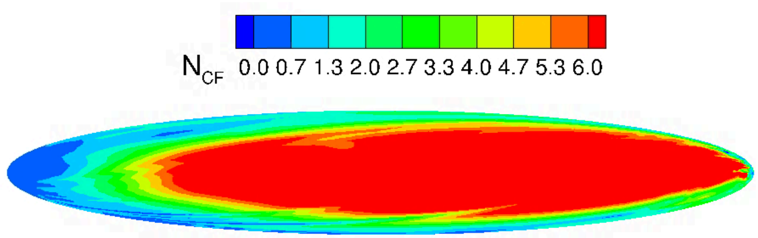
Venkatachari, B, Paredes, P., Choudhari, M., Li, F., and Chang, C.-L., "Pretest Computational Assessment of Boundary Layer Transition in the NASA Juncture Flow Model with an NACA 0015-Based Wing," to be presented at AIAA Aviation Conf. 2021.

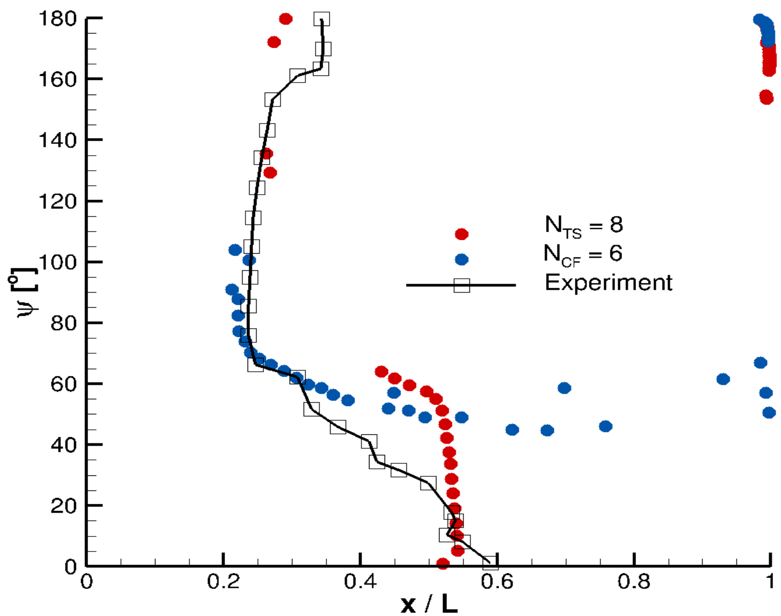
Incompressible Flow over a Prolate Sphere at Angle of Attack (Linear PSE)

Meanflow computed by OVERFLOW using SST-2003-LM2015 transition model









Experiment extracted from Krimmelbein et al. 2018.

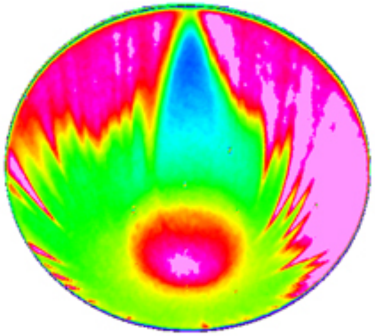
LASTRAC predictions using converted unstructured quad surface mesh

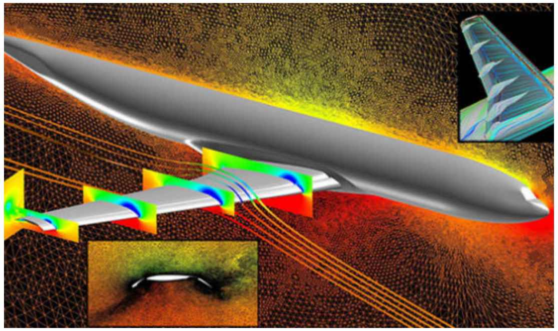
Concluding Remarks

- Physics-based transition model developed
  - Model automatically extracts wall-normal profiles, identifies instability wave, and carries out N-factor integration over the entire 3D surface using either LST or PSE
  - Transition markings on surface vertices based on preset transition N factor criterion
  - Interfaces designed to communicate with existing structured or unstructured-mesh CFD RANS solvers using a generic unstructured tetrahedral or hexahedral volume mesh and solution data structure
  - Provides a viable alternative to existing RANS-based transition models that encompasses all instability wave mechanisms
- Instability wave model and intelligent profile interpolation tool developed based on a deep-learning model
  - Can be used to improve table lookup transition model

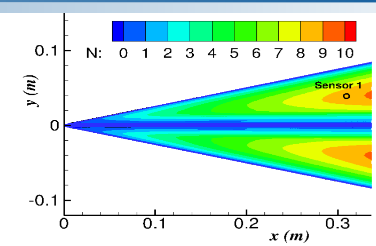
Backup Slides

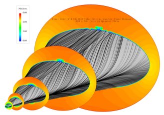
Transition Prediction in CFD Computations





https://www.nasa.gov/aeroresearch/programs/tacp/ttt/cfd-vision-2030-study/





- NASA's CFD Vision 2030 study and the Revolutionary Computational Aerosciences (RCA) subproject under T^3 identify *physics-based transition prediction and modeling* as one of the technical challenges and areas for further development
- Transition modeling in CFD solvers
  - RANS-based approach
    - Solving additional transport equations for modeled quantities to predict transition onset and turn on turbulent eddy viscosity accordingly
    - Popular due to ease of integration to existing CFD codes
  - Physics-based approach (non-RANS)
    - Table lookup using precalculated LST based disturbance growth rate curve-fitting database
      - Often still solves a transport equation to integrate N factors
    - Using either Linear Stability Theory (LST) or parabolized stability equations (PSE) approach
      - Solving a separate set of perturbation equations on a body-fitted coordinate system and perform N factor integration
      - NASA's LASTRAC transition prediction software
    - Stringent meanflow grid requirement and higher-level of expertise required
    - More compliant to transition flow physics but harder to integrate with existing CFD solvers

Instability Wave Model and Table Lookup

- Small disturbances inside the boundary layer begins to grow beyond the neutral point x_0

$$\phi'(x, y, z, t) = \hat{\phi}(x,\ y)e^{i(\beta z - \omega t + \int_{x_0}^{x} \alpha d\xi)}$$

$$N(x) = -\int_{x_0}^{x} \alpha_i d\xi$$

- When the overall amplification reaches a preset threshold value (say N = 10), flow is transitional
  - For narrowly scoped configurations, growth rate ($-\alpha_i$) with respect to disturbance frequency (ω or f), boundary-layer shape factor, displacement thickness Reynolds number, and/or crossflow Reynolds number can be curve-fitted as an instability wave model
  - For a given instantaneous boundary layer, boundary-layer parameters are calculated to query the database, and integrate N factor accordingly
  - Supersonic LFC optimization tool (Aerion Corporation) and RATTraP library (Davis et al.)
- Alternative instability wave model using machine learning
  - Improve overall accuracy
  - Broaden the scope of applications

NASA Transonic CRM-NLF Wind Tunnel Model

- Mach number = 0.856
- Upper (suction) surface, AOA $1.44°$, Re = 40×10^6/m

$$\left(\frac{N_{TS}}{8}\right)^2 + \left(\frac{N_{CF}}{4.5}\right)^2 = 1$$