NASA IV&V and Applications

Nathaniel Hildebrand and Matthew O'Connell
Computational AeroSciences Branch

David Wagner, Nelson Carvalho and Vesselin Yamakov
Durability, Damage Tolerance and Reliability Branch

E.H. Glaessgen
NASA Senior Technologist for Computational Materials

NASA Langley Research Center
Hampton, Virginia

Computable Models Review
15-16 September 2021

Approved for Public Release on 09/XX/2021
Tracking Number: 202100XXXXX

Outline

- **Modeling flow instabilities in hypersonic boundary layers with finite-rate chemistry using machine learning**
  - Performer: Brown University
  - Monitor: Nathaniel Hildebrand
- **Numerical methods to improve simulation of hypersonic turbulent flow over a compression corner**
  - Performers: Palo Alto Research Center
  - Monitors: Matthew O'Connell & Nathaniel Hildebrand
- **Computational conjugate heat transfer of incompressible flow over hollow thin rods with heated cores**
  - Performer: Galois
  - Monitor: Matthew O'Connell
- **Modeling Ti-6Al-4V *and* advanced composites: anisotropy, hysteresis, and fracture with an inferred particle system**
  - Performer: MIT
  - Monitors: Nelson V. De Carvalho & Vesselin Yamakov
- **Computational conjugate heat transfer simulation of wind tunnel model of Aerobraking for planetary (re)entry**
  - Performer: U.S. Naval Research Laboratory
  - Monitors: Matthew O'Connell & David Wagner

Outline

- **Modeling flow instabilities in hypersonic boundary layers with finite-rate chemistry using machine learning**
  - Performer: Brown University
  - Monitor: Nathaniel Hildebrand
- **Numerical methods to improve simulation of hypersonic turbulent flow over a compression corner**
  - Performers: Palo Alto Research Center
  - Monitors: Matthew O'Connell & Nathaniel Hildebrand
- **Computational conjugate heat transfer of incompressible flow over hollow thin rods with heated cores**
  - Performer: Galois
  - Monitor: Matthew O'Connell
- **Modeling Ti-6Al-4V *and* advanced composites: anisotropy, hysteresis, and fracture with an inferred particle system**
  - Performer: MIT
  - Monitors: Nelson V. De Carvalho & Vesselin Yamakov
- **Computational conjugate heat transfer simulation of wind tunnel model of Aerobraking for planetary (re)entry**
  - Performer: U.S. Naval Research Laboratory
  - Monitors: Matthew O'Connell & David Wagner

Modeling flow instabilities in hypersonic boundary layers with finite-rate chemistry using machine learning

Brown University: George Karniadakis, Tamer Zaki, Zhongqiang Zhang, & Charles Meneveau

- **Relevance to NASA's Mission**
  - High-speed boundary-layer transition increases skin-friction drag and heat flux.
    - Important for hypersonic vehicle design!
  - Modeling laminar-turbulent transition is a pacing item for the foreseeable future according to the NASA CFD Vision 2030 Study (Slotnick *et al.* 2014).
  - Research in transition modeling (Paredes *et al.* 2020) is currently supported by the NASA Transformational Tools and Technologies (TTT) Project.

- **Background Information**
  - Planar second-mode waves (Mack 1984) initiate transition to turbulence in hypersonic axisymmetric and 2D boundary layers.
  - Logarithmic amplification ratio (N-factor) of the most amplified instability mode is frequently used to estimate the location of transition onset.
  - N-factor methods require significant user expertise, relatively-high computational cost, and accurate basic states.
  - Machine learning could dramatically simplify transition modeling in practical applications and reduce the time required for transition prediction.

Monitor: Nathaniel Hildebrand

Modeling flow instabilities in hypersonic boundary layers with finite-rate chemistry using machine learning

Brown University: George Karniadakis, Tamer Zaki, Zhongqiang Zhang, & Charles Meneveau

- **Scope of the Challenge Problem**
  - Verify that DeepM&Mnet and CPINNs can accurately model canonical boundary-layer solutions with finite-rate chemistry.
  - Apply the tools DeepM&Mnet and CPINNs to model spatial linear and nonlinear instability waves (e.g., second mode).
  - Use both DeepM&Mnet and CPINNs to study receptivity of transitional boundary layers (due to freestream disturbances).

- **Benchmarks**
  - Reproduce hypersonic boundary-layer profiles from a well-established code with finite-rate chemistry (Marxen *et al.* 2011) using DeepM&Mnet and CPINNs.
  - Use machine-learning codes to reproduce a few selected results based on linear stability theory for both nonreacting hypersonic flows with shocks and boundary layers with finite-rate chemistry.
  - Extend the DeepM&Mnet and CPINNs tools to study nonlinear development of Mack-mode instability waves at finite amplitudes and the receptivity of transitional boundary layers (Li *et al.* 2012).

Monitor: Nathaniel Hildebrand

Modeling flow instabilities in hypersonic boundary layers with finite-rate chemistry using machine learning

Brown University: George Karniadakis, Tamer Zaki, Zhongqiang Zhang, & Charles Meneveau

- **Progress**
  - DeepM&Mnet and CPINNs has been shown to model hypersonic boundary-layer profiles and instability waves accurately.
  - DeepM&Mnet and CPINNs is very robust (minimal training data, adjoint problem, & different geometries).
  - NASA has been given the DeepM&Mnet and CPINNs software (along with a few example problems).
  - The monitor has run DeepM&Mnet and CPINNs.
  - The monitor has run LASTRAC (NASA in-house stability solver) to generate N-factor envelopes corresponding to second-mode waves for a flat plate at Mach 10. The results have been given to the performers so they can reproduce them with DeepM&Mnet and CPINNs.
  - The monitor is also setting up another case associated with the reentry-F cone at Mach 19.925 (Malik 2003).

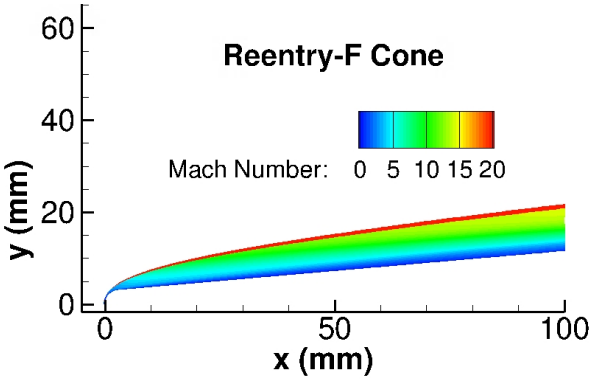
- **Future Work**
  - The monitor will compare results from DeepM&Mnet and CPINNs to results from existing NASA codes.

Monitor: Nathaniel Hildebrand

Modeling flow instabilities in hypersonic boundary layers with finite-rate chemistry using machine learning

Brown University: George Karniadakis, Tamer Zaki, Zhongqiang Zhang, & Charles Meneveau

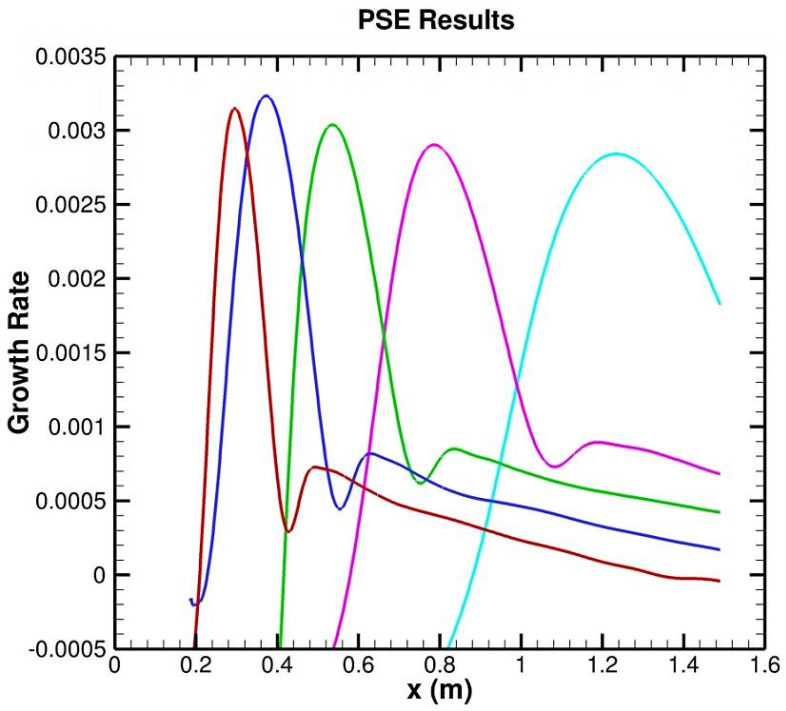
- **Updates on Tech Transfer**
  - NASA has received the machine-learning tools DeepM&Mnet and CPINNs (along with a few example problems and instructions).
  - The monitor and a NASA intern have run DeepM&Mnet and CPINNs on a few different NASA machines.
  - NASA has given LASTRAC to the performers for running stability analysis of hypersonic nonequilibrium boundary-layer flows.
  - The monitor is performing stability analysis using LASTRAC about hypersonic nonequilibrium flow over a flat plate and the reentry-F cone (Malik 2003). The results will be shared with the performers and compared against the results from DeepM&Mnet and CPINNs.
  - NASA researchers and the performers will provide basic states to one another if they are needed for verification.
  - Determine if any other pre- or post-processing scripts are needed by the monitor or performers.

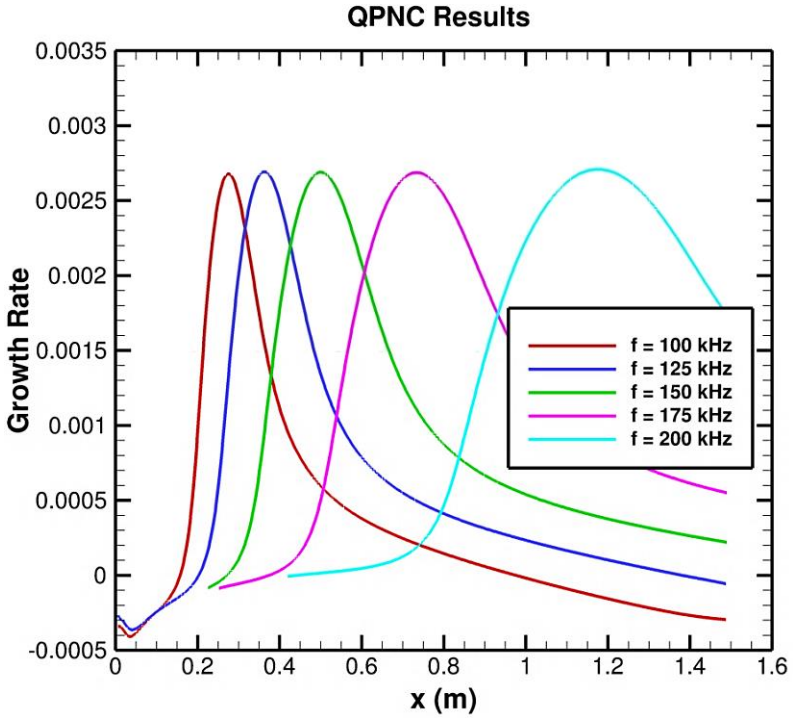


Modeling flow instabilities in hypersonic boundary layers with finite-rate chemistry using machine learning

Brown University: George Karniadakis, Tamer Zaki, Zhongqiang Zhang, & Charles Meneveau

- **Flat Plate at $M = 10$**
  - LASTRAC with chemical nonequilibrium





Monitor: Nathaniel Hildebrand

Outline

- **Modeling flow instabilities in hypersonic boundary layers with finite-rate chemistry using machine learning**
  - Performer: Brown University
  - Monitor: Nathaniel Hildebrand
- **Numerical methods to improve simulation of hypersonic turbulent flow over a compression corner**
  - Performers: Palo Alto Research Center
  - Monitors: Matthew O'Connell & Nathaniel Hildebrand
- **Computational conjugate heat transfer of incompressible flow over hollow thin rods with heated cores**
  - Performer: Galois
  - Monitor: Matthew O'Connell
- **Modeling Ti-6Al-4V *and* advanced composites: anisotropy, hysteresis, and fracture with an inferred particle system**
  - Performer: MIT
  - Monitors: Nelson V. De Carvalho & Vesselin Yamakov
- **Computational conjugate heat transfer simulation of wind tunnel model of Aerobraking for planetary (re)entry**
  - Performer: U.S. Naval Research Laboratory
  - Monitors: Matthew O'Connell & David Wagner

Numerical methods to improve simulation of hypersonic turbulent flow over a compression corner

Palo Alto Research Center: Morad Behandish & Ali Mani

- **Relevance to NASA's Mission**
  - Shock-wave/boundary-layer interactions (SWBLIs) can induce transition to turbulence in a laminar boundary layer.
    - Increases skin-friction drag and heat flux!
  - Modeling laminar-turbulent transition is a pacing item for the foreseeable future according to the NASA CFD Vision 2030 Study (Slotnick *et al.* 2014).
  - Research in high-speed SWBLIs is supported by the Hypersonic Technology Project (HTP) of the NASA Advanced Air Vehicles Program (AAVP).

- **Background Information**
  - SWBLIs occur at high speeds and on many different aircraft geometries.
  - Difficult to simulate SWBLIs because of the complicated physics (e.g., shock unsteadiness, separation and reattachment, amplification of turbulence, and heat transfer effects).
  - State-of-the-art codes that can accurately model SWBLIs have been developed and tested over many years. Can the numerical methods developed by PARC model the complicated physics well and agree with these codes?

Monitor: Nathaniel Hildebrand & Matthew O'Connell

Numerical methods to improve simulation of hypersonic turbulent flow over a compression corner

Palo Alto Research Center: Morad Behandish & Ali Mani

- **Metrics**
  - Computability – Will numerical methods created by PARC help make NASA's state-of-the-art codes easier to use and more generalizable? The monitors will determine what methods work the best.
  - Conservation & Accuracy – Can standard nondissipative numerics accurately model SWBLIs? The monitors will compare results from PARC's numerical methods with results from state-of-the-art codes used by NASA.
  - Composability & Scale Range – The problems encapsulate multiple aspects of hypersonic aerothermodynamics including shock waves, interactions between acoustic, vorticity, & entropy modes, nonequilibrium flow, and viscous/inviscid flow phenomena across a broad range of length scales.
  - Computational Speed – The monitors will determine if the numerical methods provided by PARC improve computational speed (could include parametric studies and grid adaptivity) compared to state-of-the-art codes.

Monitor: Nathaniel Hildebrand & Matthew O'Connell

Numerical methods to improve simulation of hypersonic turbulent flow over a compression corner

Palo Alto Research Center: Morad Behandish & Ali Mani

- **Progress**
  - PARC has developed an artificial bulk viscosity (ABV) method.
  - PARC and NASA have agreed on modeling hypersonic turbulent flow over a compression corner (i.e., SWBLI).
  - PARC has simulated inviscid flow over a compression corner with a shock wave and successfully compared to state-of-the-art results.
  - PARC has simulated laminar high-speed boundary-layer flow over a compression corner with their ABV method.
  - PARC has made some improvements toward automating their ABV method.

- **Future Work**
  - Compare results from different state-of-the-art NASA codes (e.g., VULCAN-CFD) to PARC's ABV method for hypersonic laminar flow over a compression corner.
    - Pressure coefficient, skin friction, etc.
  - See if the numerical methods proposed by PARC can help simplify parametric studies and grid adaptivity.
  - Extension to both transitional and turbulent SWBLIs.
  - Continue making progress toward a fully-automated solver (e.g., five constants).

Monitor: Nathaniel Hildebrand & Matthew O'Connell

Numerical methods to improve simulation of hypersonic turbulent flow over a compression corner

Palo Alto Research Center: Morad Behandish & Ali Mani

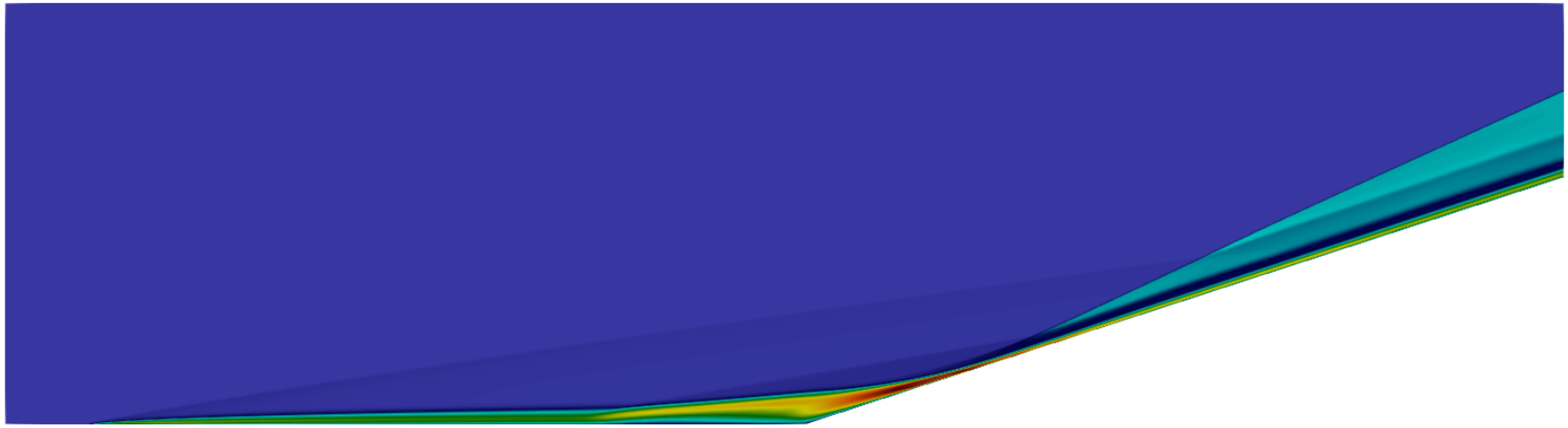
- **Updates on Tech Transfer**
  - The monitors have received descriptions of computational grids and preliminary results from PARC. NASA is computing initial solutions to compare results between the NASA and PARC codes.
  - PARC has been working on automating their ABV method so that it is more generalizable and easier for NASA researchers to use.
  - PARC will provide their numerical methods to NASA so the monitors can assess the impact on NASA codes and software.
  - NASA researchers and the monitors will provide basic states from in-house codes if they are needed by the performers.

Monitor: Nathaniel Hildebrand & Matthew O'Connell

Numerical methods to improve simulation of hypersonic turbulent flow over a compression corner

Palo Alto Research Center: Morad Behandish & Ali Mani

- **Verification in Progress**
  - Preliminary, under resolved, simulation results obtained using NASA's VULCAN-CFD.
  - Grid convergence study is in progress.



Preliminary Results using
VULCAN-CFD

Monitor: Nathaniel Hildebrand & Matthew O'Connell

Outline

- **Modeling flow instabilities in hypersonic boundary layers with finite-rate chemistry using machine learning**
  - Performer: Brown University
  - Monitor: Nathaniel Hildebrand
- **Numerical methods to improve simulation of hypersonic turbulent flow over a compression corner**
  - Performers: Palo Alto Research Center
  - Monitors: Matthew O'Connell & Nathaniel Hildebrand
- **Computational conjugate heat transfer of incompressible flow over hollow thin rods with heated cores**
  - Performer: Galois
  - Monitor: Matthew O'Connell
- **Modeling Ti-6Al-4V *and* advanced composites: anisotropy, hysteresis, and fracture with an inferred particle system**
  - Performer: MIT
  - Monitors: Nelson V. De Carvalho & Vesselin Yamakov
- **Computational conjugate heat transfer simulation of wind tunnel model of Aerobraking for planetary (re)entry**
  - Performer: U.S. Naval Research Laboratory
  - Monitors: Matthew O'Connell & David Wagner

Computational conjugate heat transfer of incompressible flow over hollow thin rods with heated cores.

Galois Inc: Eric Davis

- **Relevance to NASA's Mission**
  - Air-breathing hypersonic vehicles need to transfer excess heat caused by both aerodynamic and propulsion sources.
  - One option for cooling is to pump a thermally conductive liquid past hot components inside the vehicle.
  - Famously, the SR-71 Blackbird used fuel to transfer excess heat away from the vehicle's surface.
  - Efficient and accurate simulation of incompressible conjugate heat transfer can be used in system design.
- **Background Information**
  - A conjugate heat transfer computational problem exists in literature as a common test problem.
  - An incompressible fluid is passed at low speeds over a collection of thin-walled high density rods.
  - The core of the rods are held at a fixed temperature, and heat transfer is measured between the rod cores and the nearby fluid through the thin (1mm thick) surface of the rods.

Monitors: Matthew O'Connell

Computational conjugate heat transfer of incompressible flow over hollow thin rods with heated cores.

Galois Inc: Eric Davis

- **Metrics**

  - Computability – Will automatically generating multiple back-end configurations created by Galois help enable NASA to run code on code verification, enable robustness against still nonlinear problems, and /or enable engineering risk reduction? The monitors will evaluate Galois tool using at least two NASA simulation back-ends.
  - Conservation & Accuracy – Will there be fewer user-error defects in automatically generated configurations?

  - Composability & Scale Range – The conjugate heat transfer problem requires solving a multi-zone, multi-physics problem spanning 10^3 scales in space and 10^4 in time. Since existing solvers are being used, no difference from state of the art is expected.

  - Computational Speed – Efficiency improvements are not expected since existing solvers are being used.

Monitor: Matthew O'Connell

Computational conjugate heat transfer of incompressible flow over hollow thin rods with heated cores.

Galois Inc: Eric Davis

- **Scope of the Challenge Problem (What makes it Challenging?)**
  - Simulate incompressible fluid flow and body heat transfer for an incompressible fluid passed over multiple solid hollow rods with fixed temperature cores. Galois is simulating a 2D version of the problem.
  - The problem description is written in a high-level language that gets translated to SU2, or OpenFOAM configuration files.

- **Evaluation of Performer's Approaches Against Challenge Problems**
  - Galois have had to learn quite a lot of CFD terminology, and strategies.
  - After feedback from the last reporting session the team has significantly re-vectored the technological approach.
  - One major goal of the new approach was to more easily incorporate multiple back-end simulation capabilities.
  - Previously, the project was only capable of handling SU2. The new version has been demonstrated to generate configuration for SU2 and OpenFOAM back-ends on a single physics, single rod heat advection problem.

Monitors: Matthew O'Connell

Computational conjugate heat transfer of incompressible flow over hollow thin rods with heated cores.

Galois Inc: Eric Davis

- **Technology Transfer/Impact to NASA**
  - The Galois project could be used to have single description for simulation problems that get automatically translated to configuration files for multiple "back-end" solvers.
  - This could enable faster turn-around time for projects running multiple solvers on the same problem for either verification, robustness, or engineering confidence.
  - Galois has shared documentation to the improved language and has begun helping NASA understand how to incorporate their own solvers.
- **Future Work**
  - Galois plans to incorporate multiple physics domains towards the conjugate heat transfer problem using both OpenFOAM and SU2.
  - Galois will be sharing a preliminary version of the software with NASA. NASA plans build minimum working examples of at least two NASA CFD solvers running a test problem where all the inputs are generated from a single problem description. (Test has yet to be identified, but will be single physics CFD)

Monitors: Matthew O'Connell

Outline

- **Modeling flow instabilities in hypersonic boundary layers with finite-rate chemistry using machine learning**
  - Performer: Brown University
  - Monitor: Nathaniel Hildebrand
- **Numerical methods to improve simulation of hypersonic turbulent flow over a compression corner**
  - Performers: Palo Alto Research Center
  - Monitors: Matthew O'Connell & Nathaniel Hildebrand
- **Computational conjugate heat transfer of incompressible flow over hollow thin rods with heated cores**
  - Performer: Galois
  - Monitor: Matthew O'Connell
- **Modeling Ti-6Al-4V *and* advanced composites: anisotropy, hysteresis, and fracture with an inferred particle system**
  - Performer: MIT
  - Monitors: Nelson V. De Carvalho & Vesselin Yamakov
- **Computational conjugate heat transfer simulation of wind tunnel model of Aerobraking for planetary (re)entry**
  - Performer: U.S. Naval Research Laboratory
  - Monitors: Matthew O'Connell & David Wagner

Modeling Ti-6Al-4V *and* advanced composites: anisotropy, hysteresis, and fracture with an inferred particle system

MIT Center for Bits and Atoms: Prof. Neil Gershenfeld

- **Relevance to NASA's Mission**
  - Ti-6Al-4V (Ti64) aerospace alloy, has been identified as a key material for parts produced through additive manufacturing (AM) in aerospace industry
    - AM materials lack of suitable certification and validation procedures as requested by FAA
  - Advanced composite materials are applied across the range of NASA missions
    - Accurate damage tolerance simulation tools are deemed key

- **Background Information/Current SOA**
  - Ti64 is a light-weight alloy, with superior strength, thermal and corrosion stability. Still, its processing remains challenging and expensive.
    - AM can decrease cost and improve reliability of the Ti64 components
    - However, the challenging material processing affects the mechanical properties of the alloy, crucial for its behavior in service.
  - Composite are applied in virtually all structures where weight is a key design factor.
    - Simulating their mechanical response including failure is key to optimize designs; decrease certification time-line; simulate use cases that cannot be tested, etc.
    - Predicting the mechanical response, particularly damage tolerance and durability remains a challenge

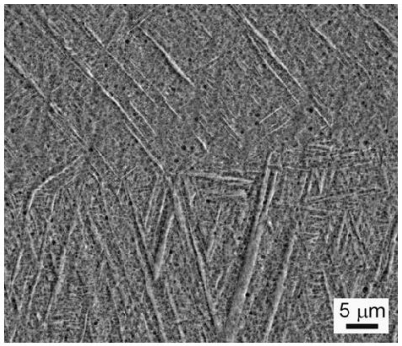
Monitors: Vesselin Yamakov & Nelson V. De Carvalho

Modeling Ti-6Al-4V *and* advanced composites: anisotropy, hysteresis, and fracture with an inferred particle system

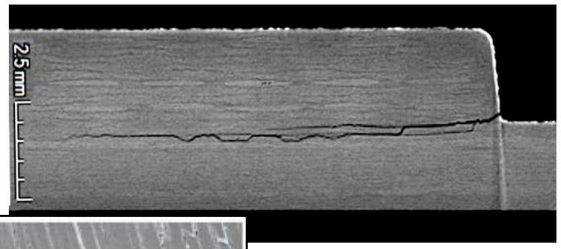
MIT Center for Bits and Atoms: Prof. Neil Gershenfeld

- **Scope of the Challenge Problem (What makes it Challenging?)**
  - Verify the reproducibility of the elastic and plastic anisotropy, and the tension–compression asymmetry behavior of Ti64 alloy.
  - Verify the effect of microstructure of Ti64 on the elasto-viscoplastic deformation and the ductile fracture in tension and torsion.
  - Verify that delamination/matrix crack interaction (key failure modes) is reproduced in composite materials (hundreds of interacting cracks).
  - Assess the ability of the approach to capture damage mechanism that involve scale coupling (micro/fiber to macro/ply), e.g. fiber kinking, and cannot, in general, be homogenized.

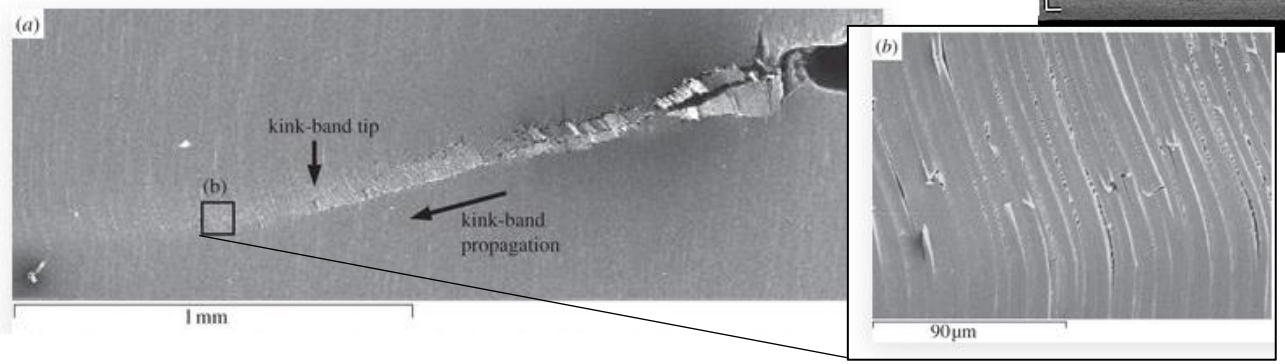
Typical Ti64 microstructure



X-ray: delamination matrix crack interaction at skin/stringer corner



Compressive failure via kinkband formation



Monitors: Vesselin Yamakov & Nelson V. De Carvalho

Modeling Ti-6Al-4V *and* advanced composites: anisotropy, hysteresis, and fracture with an inferred particle system

MIT Center for Bits and Atoms: Prof. Neil Gershenfeld

- **Initial Evaluation of Performer's Approaches Against Challenge Problems**
  - Matching elastoplastic behavior of a delrin sample in a 3-point bending test
  - Introduced directional bonding for reproducing anisotropy in materials – similar to bond-order models in atomistic force fields to represent covalent bonding in molecules.
  - Benchmark problem(s) setup in COMSOL:
    - Comparison to analytical solutions/benchmark ongoing
  - Developed module to include fiber particles and represent composite layers
  - Developed a Compact Compression numerical simulation to investigate compressive failure in composites
  - Performance scaling: multi-GPU utilization: (in particles/sec)
    CPU (10^8)→ GPU(10^9)→ projected: FPGA(10^{10}) →DICE(10^{11})
  - Raster visualization for large number of particles (dedicated renderer)

Monitors: Vesselin Yamakov & Nelson V. De Carvalho

Modeling Ti-6Al-4V *and* advanced composites: anisotropy, hysteresis, and fracture with an inferred particle system

MIT Center for Bits and Atoms: Prof. Neil Gershenfeld

- **Technology Transfer/Impact to NASA**
  - Access to Giltab. Periodic (monthly) updates.
  - Preliminary software prototype & documentation delivered to Government. Deliverable: Milestone report.
  - Link modules for simulation (parallel particle system solver), representation (functional algorithmic), optimization (evolutionary search), and evaluation (with a human in the loop). Deliverable: Linked software modules
  - Gave a presentation at High Performance Computing Community (HPCC) meeting at NASA LaRC on May 6, 2021.
  - Work performed is relevant to various ongoing NASA programs:
    - Transformational Tools and Technologies at NASA LaRC
      - AM program
      - Bondline certification
    - Revolutionary Vertical Lift Technology
    - Hypersonics Technology Project

- **Future Work**
  - The monitors will evaluate DIM3 software results against other available and published simulation studies and NASA internal experimental data.
  - Pending on the assessment above the software will be disseminated internally and applied to various ongoing NASA programs.
  - The assessment above and performance of the methodology may be documented as a formal publication.

Monitors: Vesselin Yamakov & Nelson V. De Carvalho

Outline

- **Modeling flow instabilities in hypersonic boundary layers with finite-rate chemistry using machine learning**
  - Performer: Brown University
  - Monitor: Nathaniel Hildebrand
- **Numerical methods to improve simulation of hypersonic turbulent flow over a compression corner**
  - Performers: Palo Alto Research Center
  - Monitors: Matthew O'Connell & Nathaniel Hildebrand
- **Computational conjugate heat transfer of incompressible flow over hollow thin rods with heated cores**
  - Performer: Galois
  - Monitor: Matthew O'Connell
- **Modeling Ti-6Al-4V *and* advanced composites: anisotropy, hysteresis, and fracture with an inferred particle system**
  - Performer: MIT
  - Monitors: Nelson V. De Carvalho & Vesselin Yamakov
- **Computational conjugate heat transfer simulation of wind tunnel model of Aerobraking for planetary (re)entry**
  - Performer: U.S. Naval Research Laboratory
  - Monitors: Matthew O'Connell & David Wagner



Computational conjugate heat transfer simulation of wind tunnel model of aerobraking for planetary (re)entry

U.S. Naval Research Laboratory: John Michopoulos

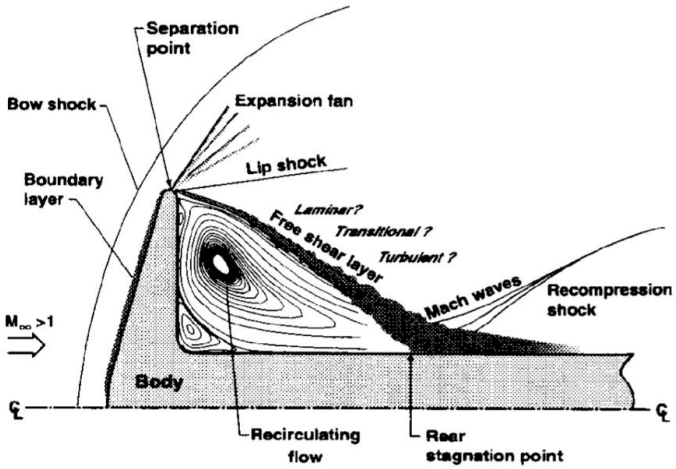
- **Relevance to NASA's Mission**
  - Non-thermally conductive materials used in thermal protection systems can be difficult to rapidly fabricate and instrument for wind tunnel experiments; while materials easier to use for experiments, such as steel, are thermally conductive.
  - Quantifying body heat transfer can help validate experiments using metals instead of ceramics or help put temporal and spatial bounds on confidence of these tests.
  - Model fabrication from metals may help reduce fabrication lead time or allow more complex instrumentation at a lower cost.
- **Background Information**
  - Historical aerobraking wind tunnel experiments were conducted with models built out of chromel, nickel and chromium (Horvath et al. 1996, 1997, & 1998).
  - Short duration experiments used to measure heating rates observed temperature increased near the vehicle payload (behind the thermal protection system).
  - If heat was conducted from the thermal protection system to the payload region the experiment would have under-predicted surface heating rates near the payload.
  - Simulation has been performed for fluid only region but has not included both fluid simulation and body heat transfer.

Monitors: Matthew O'Connell & David Wagner

Computational conjugate heat transfer simulation of wind tunnel model of aerobraking for planetary (re)entry

U.S. Naval Research Laboratory: John Michopoulos

- **Scope of the Challenge Problem (What makes it Challenging?)**
  - Simulate fluid flow and body heat transfer for an aerobraking wind tunnel model assuming a calorically perfect gas at Mach 10 in with fully turbulent flow over a 7 second duration.
  - NRL is attempting a coupled 3D simulation exceeding the initial challenge problem goal of either a strictly 2D or axisymmetric problem.
  - Use an automated multiphysics workflow with a low level of development effort.



Aerobraking wind tunnel model

- **Progress**
  - NRL has verified thermal solutions using AERO-S and COMSOL.
  - Performed grid resolution study of **both** aero and thermo grids. (previously just thermo)
  - Challenging problem required additional development:
    - Implemented rotated Riemannian flux scheme to handle strong shock instabilities.
    - Improved non-linear convergence strategies.
  - Implement direct coupling of aero and thermo grids (phantom elements)
  - Development of axisymmetric capability.

Monitors: Matthew O'Connell & David Wagner

Computational conjugate heat transfer simulation of wind tunnel model of aerobraking for planetary (re)entry

U.S. Naval Research Laboratory: John Michopoulos

- **Technology Transfer/Impact to NASA**
  - Perform independent CFD analysis of a hypersonics problem using modern simulation techniques.
  - Expand computational analysis to include thermal coupling. Internally NASA has made assumptions about heat transfer times within the vehicle body, but these have not been validated with high fidelity simulation.
  - NASA is interested in evaluating the effort required to incorporate our existing tools into the more automated workflow offered by the performer team.
  - NASA is also interested in understanding new improvements for stability and convergence acceleration for hypersonics to compare with NASA state of the art.
- **Future Work**
  - Continue running simulations to improve experimental validation.
  - Coordinate with NASA to use SU2 for the fluid solver within the automated workflow. This is a proxy for the effort required for NASA to adapt its own tools and can be done without requiring software releases from either organization.
  - Apply the metacomputing framework to recreate the automated model.
  - Evaluate results against program metrics.

Monitors: Matthew O'Connell & David Wagner