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Improvements to the Aeroheating and Thermal Analysis Code (ATAC)

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Outline

• Overview of ATAC capabilities and methodologies
• Example Cases
• New Capabilities
  – Rolling Vehicle Analysis
  – TPS Optimization
  – Burn through of ablating material layer
  – Full trajectory analysis, i.e., exo atmospheric flight
  – Particle erosion analysis
• Future Code Enhancements
ATAC Description

ATAC is an integrated aerodynamic heating/thermal response computer code used for a range of applications within the aerospace community

- Heatshield and missile TPS design
- Thermostructural analysis – provides pressure and heating boundary conditions to finite element analysis codes
- IR signature analysis
ATAC is a computer program which models the response of a flight vehicle to an aero-heating environment. The essential elements of the code are procedures to model the following:

- Geometry definition
- Freestream properties
- Inviscid flowfield
  - Surface pressure
  - Shock shape
- Boundary layer heating
- Material response and ablation
- Change in the geometry of the vehicle
Background (cont)

Additional options which may be included are:
- Particle impact erosion
- Coupled shape change / flight dynamics
- In-depth thermal response

Other factors that must be considered include:
- Efficiency
- Robustness
- Accuracy
The Aeroheating and Thermal Analysis Code (ATAC) is a state-of-the-art shape change code and includes the following models:

- Geometry model - bicubic patch
- Freestream properties - 6 environment options and 21 atmosphere models
  - 3 DOF trajectory
  - Flight
  - Wind tunnel
  - Ballistic range
  - General
  - Arc heater
Code Procedures

• Inviscid flow
  - Streamline tracing - method of steepest descent
  - Surface pressure
    • Windward - PANT Correlations, Newtonian
    • Leeward - Newtonian, Prandtl-Meyer small disturbance, separation correlations
  - Shock shape - thin shock layer global mass and momentum conservation
• Boundary layer heating - MEIT continuum solution bridged with free molecular solution
Code Procedures (cont)

- Material response and ablation - Aerotherm surface energy balance procedure
- Shape change - multi-dimensional spline fitting for bicubic patch definition
- Particle impact erosion
  - Shock layer interaction - Jaffe, Ranger-Nicholls, Reinecke-Waldman
  - Erosion - generalized G-law, carbon phenolic model, tungsten model
- In-depth thermal response at each nodal point - CMA 1D conduction with charring/ablation
Example Shapes Modeled with ATAC

2nd Generation

CAV

Apollo

Mars Science Lab
Surface Pressure

Windward
- Dahm-Love correlations developed under the PANT program
- Newtonian
- Modified Newtonian using Andrew’s correlation for subsonic flight and Vendemia’s model downstream of the tangency point

Leeward
- Newtonian, $c_p = 0$
- Prandtl-Meyer small disturbance theory
- Separation correlations
Shock Shape

Thin-shock layer integral technique
- Continuity and axial momentum equations in an integral form
- Integrands vary linearly between body and shock
- Equations solved for the shock stand off distance and shock angle

Continuity

\[ \rho_\infty u_\infty \pi R^2 = 2\pi \int_0^{\delta_s} \rho \rho u \, dr \, dy \]

Axial Momentum

\[ (p_\infty + \rho_\infty u_\infty^2)\pi R^2 = \int_0^{\delta_s} \rho u (u \cos \theta + v \sin \theta) 2\pi r \, dy + \int_0^s (p_w \sin \theta) 2\pi r_w \, ds + \int_0^{\delta_t} (p \cos \theta) 2\pi r \, dy \]
Boundary Layer Model

Momentum Equation
\[
\frac{1}{r \rho_e u_e^2} \frac{d}{ds} \left( r \rho_e u_e^2 \Theta \right) = \frac{C_f}{2} + \frac{(\rho v)_w}{\rho_e u_e^2} u_{i,w} + \frac{H \Theta}{\rho_e u_e^2} \frac{dp}{ds}
\]

Energy Equation
\[
\frac{1}{r \rho_e u_e (h_{t,e} - h_w)} \frac{d}{ds} \left( r \rho_e u_e (h_{t,e} - h_w) \Phi \right) = C_h \frac{h_r - h_w}{h_{t,e} - h_w} + \frac{(\rho v)_w (h_{t,i,w} - h_w)}{\rho_e u_e (h_{t,e} - h_w)}
\]

Entrainment Equation
\[
\rho_\infty u_\infty \bar{y}^2 = 2 r F \mu_e \text{Re}_\theta - 2 \int_0^\infty r (\rho v)_w ds
\]
Boundary Layer Model

Influence Coefficients

Basic laws were developed for incompressible flow along an impervious, isothermal flat plate. Non-ideal effects are modeled through the use of influence coefficients

\[ C_{x,y} = C_{x,y,0} \prod \left( I_{x,y,z} \right) \text{ for } x = h, f \text{ and } y = \ell, t \]

\( I_{x,y,z} \) includes models for:
- Acceleration (Pressure Gradient)
- Real gas and Mach number
- Blowing
- Surface roughness
Surface Response

Boundary Layer

Radiation Flux In

Convective Flux

Radiation Flux Out

Chemical Species Diffusion

Reaction Products

Mechanical Removal
-Melt Flow
-Particle Erosion

Char

Conductive Flux

Pyrolysis Zone

Virgin Material

Backup Material

Pyrolysis Gases
In-Depth Thermal Response

\[
\rho c_p \frac{\partial T}{\partial \theta} \bigg|_z = \frac{1}{A} \frac{\partial}{\partial z} \left( k A \frac{\partial T}{\partial z} \right) + \left( h_g - \bar{h} \right) \frac{\partial \rho}{\partial \theta} \bigg|_x + \dot{s} \rho c_p \frac{\partial T}{\partial z} \bigg|_\theta + \dot{m}_g \frac{\partial h_g}{\partial z} \bigg|_\theta
\]
In –Depth Decomposition

Three-component decomposition model:

\[ \rho = \Gamma (\rho_A + \rho_B) + (1 - \Gamma) \rho_C \]

Each of the three components decompose following Arrhenius relationship:

\[ \frac{\partial \rho_i}{\partial \theta} \bigg|_x = -B_i \exp \left( \frac{-E_{a_i}}{RT} \right) \rho_{o_i} \left( \frac{\rho_i - \rho_{r_i}}{\rho_{o_i}} \right)^{\varphi_i} \]

The present code can treat up to 30 decomposing surface and backup materials
Recent Improvements to ATAC

• Rolling Vehicle Analysis
  • Burn through of ablating material layer
  • TPS Optimization
  • Complete trajectory analysis, i.e., exo atmospheric flight
  • Particle erosion analysis (code outputs)
Rolling Vehicle Analysis

• Example case has been conducted to illustrate the benefits of rolling on reducing vehicle TPS requirements
• Mach 10 flight at 70,000 ft. altitude for 120 seconds. Angle of attack = 5 degrees
Rolling Vehicle Analysis – Heating Rates

- Even moderate angles of attack significantly increase heating conditions and recession levels
- This can result in significant increases in required TPS

Heat flux for 5 deg AOA

Heat flux for 10 deg AOA
Rolling Vehicle Analysis – Recession Levels

• Recession levels almost double for even moderate angles of attack

![Graph showing the relationship between angle of attack and recession](image)

- Recession for 5 deg AOA
- Recession for 10 deg AOA

11 inch axial position
Roll Rates Effects

• Rolling the vehicle can substantially reduce the worst case recession conditions. Requirements are driven to zero AOA levels.
• The required roll rate is a function of the total flight time at AOA. The longer at AOA the lower the roll rate requirement.
• Determination of the requirements is more complicated for a transient flight condition.
• The code is also very useful for lifting body shapes where the vehicle may be rolled ± 30 degrees, i.e., a roll position or roll rate can be specified.
• Boundary layer transition can further complicate the observed trends.
Burn Through Capability

• Earlier versions of ATAC (and CMA) would stop execution if the surface layer were removed
  – Moving grid used in surface layer
  – Different surface thermochemistry
  – Particularly troublesome for ATAC because of number of surface points, i.e., ablate through at any one point stopped the calculation
• New capability has been implemented to continue execution with subsurface material
Burn Through Capability

- Test case with silica phenolic covering carbon/carbon and aluminum
- Silica phenolic provides insulative layer for about 560 seconds.
- Carbon/carbon can provide adequate protection for a some period of time, depending on structural material used.
TPS Optimization

- New ATAC capability allows for optimization of the TPS layer based on thickness requirement (recession) or specified substrate temperature
- Capability is most useful for non axisymmetric shapes
Complete Trajectory Analysis

- Supports IR Signature Analysis
- Optical Signature Code (OSC) routines used to calculate radiant heating (exo flight) were incorporated into ATAC
Complete Trajectory Test Case

$R_n = 3.54\text{ in}$

Cone Angle 1 = 25.5°

Cone Angle 2 = 13°

Cone Angle 3 = 8°

Analysis Locations

1. 0.29 in Silica Phenolic
2. 0.78 to 0.39 in Silica Phenolic
   0.02 in Acusil IV (PHI Grid)
   0.14 in Aluminum
3. 0.79 in Silica Phenolic
   0.02 in Acusil IV (PHI Grid)
   0.16 in Steel
   0.14 in Aluminum
4. 0.39 in Silica Phenolic
   0.02 in Acusil IV (PHI Grid)
   0.14 in Aluminum
   0.24 in Cork
5. 0.14 in Aluminum

17.75 in

72.48 in
Complete Trajectory Analysis - Results

- Exoatmospheric at 148 seconds
- Reenters at 830 seconds
- Heating conditions are roll averaged

Heating Environments

Surface Temperatures
Particle Erosion Analysis G-Law

- ATAC uses a “G-Law” relationship to determine the amount of material removed by particle impact. “G” is a nondimensional parameter, where
  \[ G = \frac{\text{Mass of material removed}}{\text{Incident mass flux}} \]

- The amount of mass removed is proportional to the impact parameters, particle diameter (D), velocity (V) and incidence angle (\(\alpha\))

\[ G_{\text{mech}} = a D^b V^c (\sin \alpha)^d \]
Particle Environment

- ATAC models the environment in terms of liquid water content.
- Liquid water content is converted to drop size distribution – various distributions are available.
- Drop size effects are very nonlinear.

Rain rate (mm/hr)

Drop distribution for 69.85 mm/hr
Drop Trajectory Calculations

- Drops can break-up and distort as they cross the shock
- Drop distortion is more significant for smaller drop sizes
- Distortion is greatest aft of the stagnation region
- Drops slow down slightly after crossing the shock
Impact Environment

• Analysis tool is also used to predict incident mass flux, particle sizes, and incident angle. Extensive ground testing is required to develop material models.
Summary

• The ATAC code is continuing to evolve in response to the analysis requirements of developing aerospace systems
• Additional improvements are currently in process
  – Working with C&R to couple with Sinda. This is part of an AF SBIR program. Will also include coupling to CFD results for improved inviscid flowfield solution.
  – Shock layer radiation
  – Improvements to boundary layer transition modeling