CFD PREDICTION OF THE BEAGLE 2 MARS PROBE AERODYNAMIC DATABASE

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Overview

- Beagle 2 Mars Mission
- Aeroshell Design Approach
- Aerodynamic Database Approach
- CFD-FASTRAN Flow Solver
- CFD Analysis and Flow Features
- Static Aerodynamic Database
- Pitch Stability Analysis
- Summary
Beagle 2 Mission

- Beagle 2 Lander Part of ESA Mars Express Orbiter, Launch in June 2003
- Named After Charles Darwin’s Ship, HMS Beagle
- Martin-Baker Part of UK Beagle 2 Consortium
- Deliver Science Package to Mars Surface and Search for Signs of Life
  (Atmospheric Composition, Soil, Water, Organic Material)
Martin Baker Role in Beagle 2 Program

- Martin-Baker Responsible for Beagle 2 Entry, Descent and Landing System (EDLS)
  - Entry Vehicle
  - Parachute Deployment
  - Transonic Deceleration
  - Aeroshell Separation
  - Airbag Inflation
  - Landing
  - Airbag Release

- Previous Experience Developing Cassini/Huygens Descent Control System
Beagle 2 EDLS

- Beagle 2 Ejected From Mars Express 5 Days Prior to Entry
- Enters Atmosphere at Mach=31.5, Altitude=120km
- Aerobraking to M=1.5 Where Pilot Chute Deploys
- Main Chute Deployed at M=0.4
- Airbag Inflation
- Landing and Deployment of Experiments
Beagle 2 Aeroshell Design Approach

• Simple Generic Shape to Take Maximum Advantage of Existing Aerodynamic Data, and to Simplify Analysis
• Use of Existing Aerodynamic Databases (Huygens, Stardust, Viking, Pathfinder)
• Adoption of ballistic entry
• Minimum ballistic coefficient
• High Drag Shapes Consistent with Stability Constraints and Existing Databases (Large Angle Sphere Cone)
• Nose Radius For Minimum Mass, Maximum Drag
• Minimum Corner Radii for Maximum Drag, Limited by Structural/Thermal Requirements
• Base Diameter Maximum for Minimum Ballistic Coefficient
Beagle 2 Aeroshell Design Approach

- Constraints on Project Budget and Time to Launch Opportunity
- Reuse Existing Database
- Limited Wind Tunnel Experiments
- Apply CFD to Develop Transonic-Supersonic-Hypersonic Aerodynamic Database
- Develop Blended Aerodynamic Database From Existing Scaled Data, CFD Predictions and Wind Tunnel Experiments
Role Of CFD In Beagle 2 Development

• CFD Now Mature Enough for Reliable Use for Entry Bodies
  – Reduction of Wind Tunnel Testing Costs, Time Savings
• Martin Baker Utilize CFD-FASTRAN for Entry Body Flow Prediction
  – Static Aerodynamic Coefficient Derivation
  – Localized Flow Effects
  – Heat Flux
  – Dynamic Coefficient Derivation
• US Navy, CFDRC, and Martin-Baker Have Used CFD for a Wide Range of Escape System Related R&D
  – Seat and Occupant Aerodynamic Database Development
  – Evaluation of Seat Stability Enhancements
Beagle 2 Aeroshell Geometry

- Geometrically Similar to Huygens Probe (To Maximize Data Reuse From Huygens Program)
- Addition of Backshell Frustrum Enclosing Payload
- 60° Half Angle Blunted Cone
- Maximum Diameter D=0.9m (Huygens D=2.7m)
- Mass 60kg (17% Science Payload)
Beagle 2 Aerodynamic Database Matrix

CFD Database Matrix selected from Nominal Trajectory

- Martin-Baker 6-DoF Trajectory Code
  - NASA MarsGRAM Atmosphere
  - Newtonian Aerodynamics
  - Derived Aerodynamic Databases
  - Monte Carlo Dispersion
- Nominal Trajectory
  - Entry Angle of $\gamma = -18^\circ$
  - Altitude 120 km
- Nine Trajectory Points Selected for CFD Analysis

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<th>Mach No.</th>
<th>Velocity (m/s)</th>
<th>Temp (K)</th>
<th>Pressure (Pa)</th>
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CFD-FASTRAN Flow Solver

- Density-Based Finite Volume Formulation
- Euler and Navier-Stokes for 2D, 3D and Axisymmetric
- Multi-Zone Structured/General Unstructured/Hybrid Grids
- Chimera Overset Grids
- Laminar, Turbulent (Baldwin-Lomax, K-ε, K-ω, Spalart-Allmaras)
- Generalized Finite Rate Chemistry and Thermal Non-Equilibrium
- Roe Approximate Riemann Solver and Van Leer Flux Vector Splitting
- Explicit, Point Implicit and Fully Implicit Time Integration
- Distributed Parallel Computing Capability
CFD-FASTRAN Multi-Body Dynamics

• Fully-Automated Chimera/Overset Grid Methodology

• Fully Coupled 6-DOF Solution for Multiple Body Motion

• Closed Loop Control Models Including Autopilot, Motor Ignition/Firing, Thrust Profiles, Point Forces

• Comprehensive Output of Forces, Moments, Angular Velocities, Accelerations and Body Orientations in any User Defined Axis System

• Easy-to-use GUI for Fast Model Set-Up (Physics, Chimera Hole Cutting)
CFD-FASTRAN Thermochemistry

- Two Databases for Thermodynamics
  
  Curve fit database for 300K to 6000K
  
  Spectroscopic Database for Thermal Non-Equilibrium

- General Finite Rate Reactions
  
  Handles Arbitrary Number of Species and Reactions

- Multiple Energy Modes
  
  Thermal Equilibrium or Two-Temperature Non-Equilibrium

- Applications
  
  Entry or Re-entry Physics
  
  High Speed Missile Applications
CFD-FASTRAN Applications

- Missile Staging/Maneuvering
- Escape Systems
- Canopy Trajectory
- Aircraft Aerodynamics
- Store Separation
- Ammunition Dispenser
- Tube Launch
- Aerothermochemistry
Mars Atmosphere CFD Model

- Laminar
- Fixed Wall Temperature
- Martian Atmosphere: 97% CO₂, 3% N₂ (Mass Fraction)
- Below Mach=7:
  - Nonreacting Mixture of Thermally Perfect Gases (CO₂, N₂)
- Above Mach=7:
  - Finite-Rate Chemical Reactions
  - Eight Species (CO₂, CO, N₂, O₂, NO, C, N, O), No Ablation Products
  - Nine Reactions (Park, 1994)
- Analyze Reacting and Nonreacting Cases at Mach=7 to Verify Consistency

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<th>Mach No.</th>
<th>Angle-of-Attack (Degrees)</th>
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<td>● ● ● ●</td>
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Beagle 2 Computational Grid

- Half Body Model (180 Degree), Assume Flow Symmetry
- Resolve Shock Layer and Wake
- Avoid Grid Singularities
- Hypersonic Grid: 305,000 Grid points, 9 Domains.
- Transonic Grid: 507,000 Grid points, 9 Domains
- Near Wall Grid Clustering With $y^+$ Range of 1.0 to 5.0
Beagle 2 Grid Refinement Study

Axisymmetric Grid Refinement Study to Ascertain Grid-Independent Solution for Aerodynamic Forces

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<table>
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Validation of Aerodynamic Force Predictions Against Experiment

- 60 mm Diameter Beagle 2 Model
- Oxford University Gun Tunnel
- CO₂ gas
- Mach=6
Beagle 2 Flow Field Characteristics

Aerodynamics Affected by Shift of Sonic Line, Effect of CO₂ Gas

Evolution of Wake Over Trajectory:
Reattachment Point Moves Forward

Mach=3
Mach=10
Mach=20
Mach=28
Beagle 2 Flow Field Characteristics

- Base Flow at Mach=1.5 Unsteady
- Oscillations Result From Interaction of Separated Shear Layer and Strong Reverse Base Flow

(a) time = $t_o$
(b) time = $t_o + 0.002$ sec
(c) time = $t_o + 0.004$ sec
(d) time = $t_o + 0.006$ sec
(e) time = $t_o + 0.008$ sec
(f) time = $t_o + 0.010$ sec
(g) time = $t_o + 0.012$ sec
(h) time = $t_o + 0.014$ sec
Beagle 2 Aerodynamic Coefficients

- Newtonian Flow Approximations Hold Very Well for Mach Numbers Above 10
- Rise for Mach=28 Due to Transitional Flow (Knudsen Number=0.01)
- Transition to Half Newtonian Level in CO₂ Occurs at Lower Mach Number Compared to Air
Beagle 2 Blended Database

Several Datasets Employed in Construction of Blended Database

- Current CFD Based Data
- Huygens Phase A2 Data, Scaled to Beagle 2 (Air)
- Huygens Wind Tunnel Data (Air)
- Stardust Sample Return Capsule Wind Tunnel and CFD Data (Air)
- Mars Pathfinder Data
- Scaled NASA Experimental Data for 60° Cone (Air)

Total Angle of Attack Range from 0 to 30°, Mach Number Range from 0.4 to 28.
Beagle 2 Dynamic Stability Database

Assess Stability of Beagle 2 at Pilot Chute Release

• Well Known Pitch Instability of Blunt Bodies in Transonic Regime
• Dynamic Behaviour Driven by Unsteadiness in Base Region
• Dynamic Instability Likely to Occur Near Pilot Chute Deployment, M >1.5

Wind tunnel tests:

• Oxford University CO₂ Tunnel, Mach=2

CFD Analysis

• CFD-FASTRAN, Time-Accurate, 6-DOF
Beagle 2 Pitch Stability Experiment

- Oxford University Tunnel
- Mach=2, CO$_2$ Gas
- Model 20 mm Diameter
- Run Time Greater Than 10 sec
- Mounted on Flexible Pivot
- AoA Perturbation by Push Rod
- Model Movement Measured by Accelerometers
CFD Pitch Damping Analysis

CFD-FASTRAN Calculations

- Time-Accurate, 6-DOF (Constrained to Pitch Motion Only)
- Chimera Overset Grids: Sting Fixed, Model Moving
- Flexure Mount Resistive Torque Modeled
- Mach = 2, CO₂ Gas
- Initial Perturbation $\Delta \alpha = 2$ Degrees
- Modeled Sting/No-Sting Configurations to Assess Sting Interference Effects
CFD Based Pitch Damping Results

- Pitch Damping Analysis is **Work in Progress**
- Insufficient Data Available to Extract Damping Coefficients
- Significant Effects of Sting Interference and Flexure Mount

![Beagle 2 Pitch Damping Analysis](image)

**Beagle 2 Pitch Damping Analysis**

*Mach=2.45, CO2, Oxford University Experiment*

- Free Flight
- Sting Mounted
Summary

• CFD Has Matured to Provide Reliable Planetary Entry Vehicle Aerodynamic Predictions
• CFD Provides Substantial Time And Cost Savings
• CFD-FASTRAN Applied Over Entire Trajectory (Entry to Chute Deployment)
• Valuable Insight Gained Into Vehicle Flow Characteristics
  (Examples: Wake and Base Flow Structure, Transonic Wake Unsteadiness)
• Blended Aerodynamic Database Generated by Combining CFD Data, Scaled Existing Data, and Wind Tunnel Test Data
• CFD Based Pitch Damping Analysis Provides Insight Into Dynamic Stability Characteristics Not Easily Obtained From Wind Tunnel Tests