Application of ANSYS Workbench & CFX at NASA's John C. Stennis Space Center

Jody L. Woods
Systems Analysis & Modeling

NASA John C. Stennis Space Center
Overview

- SSC Background Info
  - Who We Are & What We Do
  - Test Facilities / Capability

- Analysis Activities at SSC
  - Systems Analysis & Modeling
    - Diverse Range of Analysis Types
    - Analysis Tools Used

- ANSYS Workbench / CFX Applications
  - Recent Examples of ANSYS Workbench Analyses
  - Future ANSYS Workbench & CFX Capability Assessment
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Stennis Space Center Background Info
SSC – Who We Are & What We Do

One of NASA’s 10 Field Centers; The Nation’s Premier Rocket Propulsion Test Facility and Home to the Applied Research & Technology Office

- **Engineering & Science Directorate (E&SD)**
  - Responsible for the safe operation of one of a kind national test facilities valued at over $2 billion
  - Oversight of several rocket engine propulsion test programs such as Space Shuttle Main Engine acceptance testing and Constellation Systems J-2X engine testing for NASA’s next generation of rockets for Lunar and Mars exploration

- **Applied Research & Technology Project Office (ARPTO) and the Science and Technology Division (S&TD)**
  - Conducts scientific research focused on extending results of NASA Earth-Sun system sciences beyond science and research communities to contribute to national priority applications with societal benefits
  - Maintains scientific and engineering laboratory capabilities to support ocean color remote sensing, calibration/validation for coastal remote sensing and modeling products, algorithm development, and sensor development to support scientific and propulsion testing applications

- **Innovative Partnership Program (IPP)**
  - Consists of Small Business Innovative Research and Small Business Technology Transfer (SBIR/STTR) programs, Intellectual Property Management (IPM), and the Dual-Use Technology Development Program
  - Provides leveraged technology investments, dual-use technology partnerships, and technology solutions for NASA through partnerships with industry, academia, and other agencies

SSC Tests A Wide Variety of Engines and Test Articles over a Broad Range of Test Propellant Conditions, Facilities, and Configurations
SSC Rocket Propulsion Test Facilities

**E-1 Test Stand**
- 3 Test Cells
- Ultra High Pressure Blow-Down Propellant Delivery (15k psi)
- Full-Scale Engines & Components (Up to 1.2M lbf Thrust)

**E-2 Test Stand**
- 2 Test Cells
- Ultra High Pressure Blow-Down Propellant Delivery (15k psi)
- Mid-Scale & Small-Scale Engines & Components (Up to 120K lbf Thrust)

**E-3 Test Stand**
- 2 Test Cells
- High Pressure Blow-Down Propellant Delivery
- Small-Scale & Sub-Scale Engines & Components (Up to 60K lbf Thrust)

**A-1 & A-2 Test Stands**
- 1 Test Cell Each
- Low Pressure Run Tank Propellant Delivery
  Full-Scale Engine Development & Certification (Up to 1.7M lbf Thrust)

**B-1/B-2 Test Stand**
- 2 Test Cells
- Low Pressure Run Tank Propellant Delivery
  Full-Scale Engine / Stage Development & Certification (Up to 11M lbf Thrust)
SSC – Complete Suite of Test Capability and Expertise at One Site

SSC Rocket Propulsion Test Support Facilities

Cryogenic Propellant Storage Facility
- Six 100,000 Gallon LO2 Barges
- Three 240,000 Gallon LH2 Barges
- 600,000 Gallon LH2 Storage Sphere

High Pressure Industrial Water (HPIW)
- 330,000 gpm Delivery System

High Pressure Gas Facility (HPGF)
- GN, GHe, GH, Air: ~ 3000 to 4000 psi

Additional Support
- Laboratories
  - Gas and Material Analysis
  - Measurement Standards and Calibration
  - Environmental Measurements & Analysis
- Fabrication & Maintenance Shops
- Site Utilities
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Analysis Activities at SSC
SSC – Systems Analysis & Modeling

Diverse Range of Problems Analyzed to meet Responsibilities for Facility and Test Program Design, Operations, and Maintenance

- **Structural**: Piping Systems, Components, and Test Stand Structures, Linear & Non-Linear Stress, Modal, Structural Dynamics, Contact, Structural Stability
- **Fluids**: Liquids, Gases, -420°F to 6000°F+, Near Vacuum to Ultra High Pressures, Incompressible, Compressible, Piping Networks, Complex 3D Internal and External Flows, Chemical Reactions, Cavitation, Flow Instabilities, Multi-Phase Flow, Boiling, Free Surfaces
- **Thermal**: Structural Heat Xfr with Conduction, Convection, and Radiation, Piping System Network Analysis
- **Multi-Physics**: Thermal Stress, Conjugate Heat Xfr Involving Conduction and Radiation, Fluid Structure Interaction

We have developed a suite of effective analytic modeling and analysis tools providing high fidelity assessment of test stand performance; our tools include:

- Rocket Propulsion Test Analysis (RPTA) Model, a 1D propellant system analyzer
- Spreadsheet & MathCad-Based Analysis Routines for Orifice Sizing, Pressure Drop/Valve Sizing & Protuberance Analysis (RTD in Pipes), etc.
- Piping Network Flow & Heat Transfer Analysis (FlowMaster, SINDA)
- Piping System Structural & Code Compliance Analysis (AutoPIPE)
- **CFD Used for Select Propulsion Test Situations** (CRUNCH, **CFX**)
- **Finite Element Structural, Thermal, and Multiphysics Analysis** (**ANSYS/CFX**)

Growing our Capabilities

- Procured ANSYS Mechanical, Pro-Engineer Import Module and 1 year lease of CFX Mesh, CFX Full Capability Solver, CFX Post, and CFX Parallel in Oct. ‘06
  - “Filled the Gaps” in our analysis tool suite
  - Assess CFX & Workbench/CFX capabilities relative to our needs
SSC – Integrated Facility Simulation & Analysis

Where We Are Now
FY-06/07 Capability Development Initiatives

- Improved DDMS
- Record Retention System Development
- Drawing Tree Development
- Pro/E model MSK capability
  - A CM enhancement opportunity
- Wider (Extra-EA30) access to analytic models
- PITV Project
  - GUI
  - Server Access
- Instituted EA30 Internal Technical Reviews

Where We Were Before '06

- RPTA Model
- CFD Crunch/FDNS
- Fanno Model
- MathCad/Excel Models
- AutoPIPE Piping Systems

Test Data Analysis Process Improvements

- ANSYS Workbench with CFX
  - Structural Stress & Thermal Analysis
  - Piping System and Test Stand Modal and Dynamics Analysis
  - Conjugate Heat Transfer Analysis
  - Fluid Structure Interaction Analysis
  - Advanced Computational Fluid Dynamics Analysis
  - FlowMaster by FlowMaster, Inc.
  - Purge systems design and analysis
  - SINDA
    - System Network Thermal Analysis

Analysis Tool Suite Growth

- A&B Stand Modeling & Analysis
- Operations Support
  - Activation & Test
- Facility Operations Support, e.g., in FY06
  - LH2 Barge RD issue
  - HP Air System Contamination
  - LH2 Sphere Bypass Design
  - UT inspection of B Stand HP Water Deluge Sys
  - E1 LO2 Butterfly Valve Investigation

Broader/More Comprehensive Engineering Support

- CBS Test Stand Design
- KSC LO2 Tank Analysis
- RS-68 Test vs. Flight Performance Variation

ANSYS Workbench with CFX Promises a Substantial Increase in Physics Based Analysis Capability
SSC – Integrated Facility Simulation & Analysis

Stennis Space Center

Analytical Tools Available for Test Facility/Project Analysis, Simulation, & Modeling
- Comprehensive Propellant System Thermodynamic Modeling & Test Simulation
- Comprehensive Structural / Thermal / Fluids Modeling Expertise & Capability

Integrated Performance Modeling Capabilities Substantially Improves Understanding & Knowledge of Test Systems Performance that has Translated to Efficient Test Facility Design, Activation, & Test Operations

System Design

System Modeling

Structural Stress, Dynamics, and Heat Transfer Analysis

Fluid, Thermal, and Thermodynamic System Network Analysis

CFD Modeling & Analysis

Test & Data Analysis; Model Verification & Validation

Predicted (-) vs. Actual (o)

UHP Bottle Pressure

Interface Pressure

TIME SECONDS

Distance from Discharge (ft)

Luminous Flame

Wind
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Recent Examples of ANSYS Workbench Analyses
14” LOX Valve Thermal Analysis

- 26,000 lb LOX Valve for flow isolation of Ultra High Pressure LOX system
- Valve was cryo flow tested prior to installation in order to mitigate costly installation & removal if it did not work correctly
- FE thermal-structural model developed to validate ANSYS with cryo flow test data and assist in redesign

<table>
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<tr>
<th>Geometry</th>
<th>Description</th>
<th>Analysis</th>
<th>Model</th>
<th>Loads &amp; Boundary Conditions</th>
<th>Validated Results, thus Methodology Validated</th>
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- Measured Steady-State Frost Line
- Measured Valve Heat Load: X BTU/Hr
- Predicted Steady-State Frost Line
- Predicted Valve Heat Load within 1% of X

Pro-E Solid Model

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<th>Boiling LN2 Convective Film Coefficient</th>
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<td>Bulk Temp - Surf Temp</td>
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- NIST / MIL-HDBK Temperature Dependent Material Properties
- Empirically Based Temperature Dependent Boundary Condition Parameters
- Radiation, Boiling, Convection, Natural Convection

Von-Mises Stress Total Deformation
Thrust Takeout Structure Modal Analysis

- Existing thrust take-out structure being modified for new test program
- Customer needed natural frequency predictions for modified structure
- Developed ANSYS Workbench models of current and new structure for modal analysis

- Measured frequency response of current structure to impact loading at specific locations
  - Overall agreement with prediction was good
- Validation of model with experimental data added level of confidence to predictions for new structure
Ultra High Pressure (15K psi) GN2 Spool Piece Misalignment

- Double 90° bend spool-piece for new UHP GN2 Bottle didn’t line up
- Proposed mitigation was to heat specific area in the field such that resulting permanent deformation would result in alignment after return to ambient temperature
- ANSYS Workbench used to conduct transient thermal and plastic deformation analyses for several sets of process parameters, i.e. location and area of heat application, duration, max temperature, etc.
- Determined that proposed method would be infeasible
  - Attaining desired deformation would require complex and precise process parameters, multiple locations of heat application, and post-operation stress relief heat treatment
  - Recommended cut-and-weld procedure to achieve precise alignment
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Planned ANSYS Workbench / CFX Capability Assessment
SSC – Planned Future ANSYS Workbench / CFX Analyses

Blow-Down Run Tank Cryo-Collapse & Propellant Contamination

• **Blow-Down Run Tanks** supply propellant to tests; as pressurant is fed in through the top, the propellant is forced out the bottom
  – Cryo-Collapse is sometimes exhibited
  – Propellant Contamination occurs

• **Analyzing and predicting these phenomena is very complex**
  – Heat Transfer between walls and fluid and between gas and liquid
  – Multi-Phase with transition from superheated gas to compressed liquid and the reverse
  – Going from ambient pressure, sub-critical conditions to ultra-high pressure super-critical
  – Free surface and droplets when sub-critical
  – Heat transfer associated with boiling, condensation, and vaporization

• **In-House CFD tools don’t capture all applicable physics**
  – ANSYS/CFX will be used to check in-house code results
LH2 Storage Sphere Boil Off

- **50,000 Gallon Vacuum Jacketed LH2 Storage Sphere**
  - Low pressure inner tank supported with light stand-off structure
  - Perlite fill within vacuum jacket suppresses radiative heat transfer between inner and outer tanks; Perlite settling results in area at top of tank with full radiative heat transfer
  - Constant GH2 boil-off due to heat leakage into LH2
  - At low fill levels significant thermal gradient may exist between tank bottom and top; could result in damage to support structure and shifting of perlite and/or inner tank

- **Need to determine if there exists a minimum critical tank fill level that precludes excessive tank support stress from thermal gradients**
  - Conjugate heat transfer analysis with liquid, gas, and solid domains involving conductive, convective and radiative heat transfer
  - Boiling liquid and temperature stratification of gas within inner tank
  - As LH2 boils off and lowers fill level, assess $\sigma$ and $\delta$ vs. fill level
Plume Impingement Heating with Water Cooling

- Rocket Engine exhaust plumes often impinge on concrete tarmac or a steel “flame bucket” that redirects a vertical plume horizontally
  - Water cooling is required in areas of impingement

- Capability needed to rapidly and accurately predict amount of cooling water required, adequate injection hole pattern, heat load on structures, etc.; particularly for new test programs / new construction
  - Conjugate heat transfer including radiation
  - Subsonic & supersonic flow
  - Chemically reacting flow
  - Multiphase flow with boiling
LN2 Pump Parametric Study

• Existing positive displacement LN2 pump system at High Pressure Gas Facility does not perform to specifications and requires excessive maintenance; slated to be replaced with new equipment

• Pumping efficiency very sensitive to fluid quality due to vaporization / cavitation of fluid within cylinders on inlet stroke
  – Results in less than positive displacement performance
  – Results in excessive heating of fluid and wear of components

• Parametric study using ANSYS proposed in order to arrive at best design given the range of fluid inlet conditions expected
  – Conjugate heat transfer
  – Fluid structure interaction
  – Multiphase flow with cavitation
  – Parameterized bore, stroke, RPM, etc.; Range of fluid inlet conditions
  – Assess pumping efficiency vs. parameters to arrive at optimum design
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Summary

• NASA’s John C. Stennis Space Center – Who we are & What We Do
  – The Nation’s Premier Rocket Propulsion Test Facility; We Test A Wide Variety of Engines and Test Articles over a Broad Range of Test Propellant Conditions, Facilities, and Configurations

• Analysis Activities at SSC
  – Diverse Range of Problems Analyzed to meet Responsibilities for Facility and Test Program Design, Operations, and Maintenance
  – We have developed a suite of effective analytic modeling and analysis tools
  – Growing our capabilities; acquired ANSYS Workbench / CFX as part of development initiative

• Examples of tasks already undertaken using ANSYS Workbench
  – Thermal / Structural Analysis Validated with Experimental Data
  – Modal Analysis Validated with Experimental Data
  – Transient Heat Transfer and Thermal Stress with Plastic Deformation
  – ANSYS Workbench has been very useful and has lived up to expectations

• Examples of capability evaluation planned using ANSYS Workbench & CFX
  – Conjugate Heat Xfr with Multiphase flow, very complex thermodynamics, liquid free surface and droplets; physics not solvable by in-house CFD codes
  – Conjugate Heat Xfr w/ Radiation / Thermal Stress, Multiphase Flow, Boiling, Buoyancy
  – Conjugate Heat Transfer Xfr w/ Radiation, Multiphase Flow, Boiling, Subsonic & Supersonic Flow, Chemically Reacting Flow
  – Parametric Study involving Conjugate Heat Transfer, Multiphase Flow with Cavitation, and Fluid Structure Interaction
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Questions / Discussion

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