October 1998
Working Group Meeting on Heavy Vehicle Aerodynamic Drag: Presentations and Summary of Comments and Conclusions

Rose McCallen, Walt Rutledge
Don McBride, Kambiz Salari
Fred Browand, Anthony Leonard
Jim Ross, Bruce Storms
J.T. Heineck

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October 1998
Working Group Meeting on
Heavy Vehicle Aerodynamic Drag:
Presentations and Summary of Comments and
Conclusions

Jointly written by

Lawrence Livermore National Laboratory
Sandia National Laboratories
University of Southern California
California Institute of Technology
NASA Ames Research Center

Introduction

A Working Group Meeting on Heavy Vehicle Aerodynamic Drag was held at NASA Ames Research Center, Moffett Field, California on October 22, 1998. The purpose of the meeting was to present an overview of the computational and experimental approach for modeling the integrated tractor-trailer benchmark geometry called the Sandia Model and to review NASA's test plan for their experiments in the 7 ft x 10 ft wind tunnel. The present and projected funding situation was also discussed.

Presentations were given by representatives from the Department of Energy (DOE) Office of Transportation Technology Office of Heavy Vehicle Technology (OHVT), Lawrence Livermore National Laboratory (LLNL), Sandia National Laboratories (SNL), and NASA Ames Research Center.

This report contains the technical presentations (viewgraphs) delivered at the Meeting, briefly summarizes the comments and conclusions, and outlines the future action items.
Overview of the Project, Current Funding, and Future Workshop

An overview of the project was presented by Rose McCallen of LLNL. The viewgraphs are enclosed.

Jules Routbort from Argonne National Laboratory attended the meeting as the DOE OHVT representative and presented the funding situation for this effort. Table 1 summarizes the project funding.

**TABLE 1. Funding**

<table>
<thead>
<tr>
<th></th>
<th>FY 98</th>
<th>FY 99 ($ distributed to date)</th>
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<tbody>
<tr>
<td>LLNL</td>
<td>$100K</td>
<td>$170K ($100K)</td>
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<td>SNL</td>
<td>$100K</td>
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<td>Caltech</td>
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<td>NASA</td>
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<tr>
<td>Totals</td>
<td>$325K</td>
<td>$435K ($290K)</td>
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</table>

NASA requested that their FY 99 allocation be distributed as soon as possible to cover testing costs.

It was noted that the current budget does not provide funds for the Fall 99 Workshop. LLNL policies do not allow commitment to a location and date without the required funds in hand. It was suggested that the Workshop be scheduled in conjunction with the SAE Truck and Bus Conference, Detroit, Michigan in November 1999. Jules Routbort supplied a contact in the DOE/OHVT that is affiliated with SAE that could possibly provide assistance.

Computational Issues Related to the NASA Experiment

An overview of the Reynolds-averaged Navier Stokes (RANS) modeling being performed by SNL was presented by Kambiz Salari. Current efforts involve the modeling of past experiments on the Sandia Model performed in the Texas A&M wind tunnel. For these RANS simulations the computational field extends to the wind tunnel walls with slip boundary conditions (no penetration) at the walls. The computational meshes for the RANS simulations range from 10 to 30 million zones.

The large-eddy simulation (LES) approach being used by LLNL was presented by Rose McCallen. Issues related to boundary conditions, subgrid-scale modeling, and data analysis were discussed. It is anticipated that the converged LES solution will require finer mesh discretization than the RANS solution. Proposals to reduce the extent of the computational domain by moving boundaries closer to the model, away from tunnel walls, were criticized with warnings that this can introduce approximately 2.5% error in the solution.
Also stressed was the importance of having the time variation of the three velocity components for LES model validation, which will be provided by the NASA experiments in the truck wake.

Further discussions on LES involved wall modeling (i.e., approximations at walls to reduce discretization requirements). Kambiz Salari of SNL has information on a method he called ODT. He will provide the reference to the team.

**NASA Wind Tunnel Test Plan**

Bruce Storms presented NASA's test plan for the experiments on the Sandia Model in the 7 ft x 10 ft wind tunnel scheduled for January 1999, and J.T. Heineck presented information on the particle image velocimetry (PIV) measurements planned for the test. Their presentations are enclosed. There were informal discussions with NASA's Dave Driver on his oil film interferometry technique (OFI) for measuring skin friction and with NASA's James Bell on his pressure sensitive paint (PSP) measurements. These techniques will also be used in the wind tunnel tests. Afternoon activities included wind tunnel tours.

The viewgraphs from the formal presentations provide details on the wind tunnel dimensions, measurement accuracies, and the test plan. The specific issues raised during the presentations and informal discussions are reviewed below.

The wind tunnel test section is 15 ft long, 10 ft wide, and 7 ft high. There is a 1% divergence on the side walls only. The front end of the vehicle will be placed approximately 6 inches from the wind tunnel contraction section where the two-dimensional time-averaged inlet velocity profile will be provided. It was suggested that by using a potential flow calculation, this inlet profile could be projected farther upstream for use as the inlet condition to the computational models. In this way the blockage effects by the vehicle will be more accurately captured. The boundary layer thickness at the beginning of the 7 ft x 10 ft test section is 2.1 inches and the displacement thickness is 0.6 inch. The streamwise growth of a turbulent boundary layer can be estimated as 1% of the run.

The model is mounted on four 1 inch cylindrical posts so that the base of the truck is 3 inches from the tunnel floor. Fairings will be placed around the posts to seal the floor openings, as was done in the Texas A&M tests. The fairings are also cylindrical with approximately a 1/8 inch gap between the posts and fairings. The fairings contribute are expected to significantly disturb the body underflow and thus, should be included in the calculations.

The proposed test conditions are 200 mph wind velocities for a Reynolds number (Re) of 2 million and a Mach number (Ma) of 0.27. This wind velocity corresponds to a full size truck traveling at approximately 24 mph. Concerns were raised as to the high Mach number flow (i.e., compressibility effects are usually negligible below Ma of 0.1). The necessity for the high flow velocities stems from the need to improve the accuracy of the PSP and increase the loads for the facility balance measurements. Higher velocities result in higher pressures which improves the accuracy of these measurements. The PIV accuracy is not dependent on the velocity magnitude in the range of interest. Since the ultimate goal
is to obtain data for validation of our computational incompressible flow models, it was suggested that if a range of Re can be considered, possibly one case at or below Ma of 0.1 be included (i.e., approximately 74 mph winds in tunnel, Re = 740,000, and real truck speed of approximately 10 mph).

It is expected that 2 yaw angles (e.g., 5 and 10 degrees off of center) will be attempted for PSP and OF1 measurements and 1 yaw angle for the PIV measurement. The reduction of yaw angles for the PIV measurements is due to the excessive setup time for each yaw angle change compared to the setup time for the other measurement techniques. For validation of the computations, we would prefer to have the more significant change in flow characteristics caused by a 10 degree yaw. However, if more data can be acquired for the reduced angle of 5 degrees, this smaller angle may be a better choice. The NASA team will take a closer look at these issues and provide more information to make the optimum choice. The drag at 0 degrees and each yaw angle will be measured and the wind averaged drag (i.e., drag averaged over yaw angles) will be calculated from this limited sample.

The PIV measurements will be taken in the model wake, providing the three components of velocity in the plane of a laser sheet. Two options were presented for the orientation of the laser sheet. The first choice is to position the laser sheet normal to the stream and choose slices over a 13.5 inch distance behind the model in the streamwise direction. The second choice is to position the laser sheet in the streamwise direction and sweep along the direction normal to the flow, keeping one side of the sheet as close as possible to the backend of the model. With the first choice, it will be difficult to determine streamwise effects because the results in the streamwise direction are measured at different setups and matching the phase of the solution will be difficult. However, streamwise normal vortical roll ups will be observed directly. The second choice will more clearly provide the time evolution of vortices, but the difficulty will be to patch together the picture of the flow in the cross stream direction. The ideal solution may be to provide results from both setup options but settle for less data in each configuration. NASA's J.T. Heinech will further investigate the possibility of acquiring results at both orientations by limiting the yaw angle and piggy back on experiments directly following our test that require an alternate laser sheet orientation.

The PSP measurements will provide time averaged pressures. There was some discussion on obtaining time-dependent pressures with PSP, since the camera has a 20 Hz sampling rate (at ±7 psf accuracy). However, setting up for time-dependent measurements by January would be a stretch.

The OF1 technique can supply quantitative time-averaged skin friction measurements. The technique requires a shiny surface, which is obtained by applying mylar to the model surface. It was suggested that for this test the OF1 measurements be used to determine the separation and reattachment positions on the floor of the tunnel in the wake of the model, since hot-film measurements of skin friction are already going to be measured on the model body. Skin friction measurements on the model body will be provided by Taos hot-film system which can detect flow separation, reattachment, and transition. In the 0 degree (no yaw) case, it is expected that the boundary layer on the top and side walls of the model will transition around the midsection of the model. The approximate locations of separa-
tion and reattachment positions for each of the 2 yaw angles are needed to determine the
best positions for the hot-film system. This information is not available from the past
Texas A&M tests nor from previous SNL RANS computations.

To summarize, many of the questions raised were either resolved at the meeting or some
guidance was provided to the NASA experimental team so that decisions can be made on
optimum instrument positioning or desired flow conditions. However, the question that
still requires a timely answer from the computational team is what are the optimum posi-
tions for the hot-film system for skin friction measurements of separation, reattachment,
and transition. A one month lead time is needed for any moderate experiment changes
from the current test plans.

Future Meetings

The next meeting will take place via conference call and will again focus on the NASA 7
ft x 10 ft wind tunnel tests. This meeting should be held before December 1, 1998 to pro-
vide 1 month lead time for modifications in the tests scheduled for January 1999. It is
expected that several of the Truck Aero Team members will be interested in visits to
NASA to observe the actual testing in January 1999.

Action Items

The follow-on prioritized action items with the individuals responsible for the tasks are as
follows:

1. Provide guidance for positioning hot-film system for skin friction measurements.
   Kambiz Salari of SNL will investigate the possibility of running a 5 or 10 degree yaw
case with the RANS model. (R. McCallen and K. Salari)

2. Provide NASA with the size of the fairings to be placed on the supporting cylindrical
   posts. (K. Salari)

3. Reevaluate times for laser sheet and camera positioning for various yaw positions and
   laser sheet orientations to assist in developing a prioritized list of measurements for
   PIV. (J.T. Heineck and B. Storms)

4. Provide references on NASA's PIV techniques to be used in our experiments. (J.T.
   Heineck)

5. Detailed description of 7 ft x 10 ft wind tunnel. (B. Storms)

6. Provide reference on wall modeling method for LES. (K. Salari)

7. Call SAE contact in DOE/OHVT for assistance with scheduling of Fall 99 Workshop
   with the SAE Truck and Bus Conference. (R. McCallen)

8. Setup conference call and agenda for next meeting. (R. McCallen)
Truck Aero Team Meeting
NASA Ames, CA
October 22, 1998

Attendee List

<table>
<thead>
<tr>
<th>Attendee</th>
<th>Organization</th>
<th>e-mail address</th>
</tr>
</thead>
<tbody>
<tr>
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<td>NASA Ames</td>
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- Agenda -

Truck Aero Team Meeting

NASA Ames, CA

October 22, 1998

Purpose of Meeting

Present computational and experimental approach
Review experimental test plan
Discussions and sharing of ideas

Introduction

Project Overview (Rose McCallen, LLNL)
Budget (Jules Routbort, DOE/ANL)

Computational Work

RANS Modeling (Kambiz Salari, SNL)
LES Modeling (Rose McCallen, LLNL)

Experimental Work and Test Plan

Test Plan and Instrumentation (Bruce Storms, NASA)
Particle Image Velocimetry Measurements (J.T. Heineck, NASA)
Wind Tunnel Tour

Wrap-up Discussion

Next Progress Meeting
Near Term Action Items
Aerodynamic Design of Heavy Vehicles

Overview of Project

Rose McCallen, Ph.D.

Lawrence Livermore National Laboratory, Livermore, CA

October 1998
The MYPP is based on industry needs and consideration of current technology, funding, and DOE interests.

DOE and National Laboratory interest
- Reduce heavy vehicle drag -> reduce fuel consumption and emissions
- R&D for DOE programs

Industry needs
- Advanced computational tools and experimental methods
  - Understand the effects of design changes
  - Simulate fully-integrated tractor-trailers
- Design improvements for drag reduction

Current technology - CFD is hard!
- Reynolds-averaged Navier Stokes (RANS) is common approach
- Large-eddy simulation (LES) is in development
- DPIV measurements can provide full velocity field measurements

Funding is minimal and we need a plan with a 'near-term impact'
- FY99: $540K (= 85% of requested $635K)
The MYPP focuses on development and demonstration of a simulation capability.

Trucking Industry Participation → DOE, Univ, Lab Participation

- Computation & Experimental Data Bases
  - Establish Benchmark Geometries
    - Experiments
      - Moderate & High RE Forces, Pressures, & Whole-Field Velocity Yaw
    - Computations
      - RANS & LES
      - Vortex, FE, & FD
      - Other

- Evaluation of Current & New Technologies
  - Literature, Documents, & Data Reviews
    - Identify Possible Solution Strategies for Tractor-Trailer Aero Improvements
      - Recommendations & Reports

Validation
Near-Term Impact: Comparison of RANS and LES and detailed experimental verification for a real truck problem.

Sandia’s Model

Advantages
Simple geometry with some existing data and some modeling already done
The final detail results will be available for comparison to commercial tools
Each organization's contributions are critical to the project's success.

**Computational Modeling**

- Rose McCallen (PI)
  - Large-Eddy Simulation using Finite Element Methods
  - Caltech (California Institute of Technology)

**Experimental Modeling**

- Don McBride
  - GTS Experiments at Texas A&M

- Walt Rutledge
  - Moderate Speed Experiments in Wind Tunnel

- Anthony Leonard
  - Large-Eddy Simulation using Vortex Methods
  - USC (University of Southern California)

- Fred Browand
  - Moderate Speed Experiments in Wind Tunnel

- Jim Ross
  - High Speed Experiments in 7'x10' and 12' Wind Tunnels

- Don McBride
  - Sandia National Laboratories

- Walt Rutledge
  - Sandia National Laboratories

- Reynolds-Averaged Modeling using Finite Difference Methods
  - National Aeronautics & Space Administration
Our near-term tasks have been identified and prioritized.

Benchmarks

1. Sandia Body
   Experiments
   - Texas A&M, Re = 1,600,000
   - NASA 7’x10’, Re = 1,600,000 and other moderate to lowest Re
     Oil film interferometry, particle image velocimetry, doppler global velocimetry
     Upstream mean velocity profile provided
     0, 5, and 10 degree yaw conditions
   - USC wind tunnel, two Re conditions within 200,000 < Re < 400,000
     With and without trailer/tractor height mismatch and gap
   Computations
   - RANS for high and low Re (SNL)
   - LES for low Re with some attempt at high Re (LLNL and Caltech)

2. New Model Design (USC)

3. Gene’s Model for Re sensitivity study (i.e., how high is enough and drag delta’s for components)
   - NASA 12’, Re_{max} = 5,000,000, model with and without components
Our budget is not consistent with projected funding.

**FY99 budget : $540K**

<table>
<thead>
<tr>
<th></th>
<th>Computations &amp; Experiments</th>
<th>Evaluation of Current &amp; New Technologies</th>
<th>Final Report</th>
<th>Total/Year</th>
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<td>TOTAL</td>
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<td>$5,734K</td>
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It was necessary to leverage other funding sources.

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<tr>
<th>Institution</th>
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<td>SNL</td>
<td>- past data obtained at Texas A&amp;M</td>
<td>Free</td>
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<tr>
<td></td>
<td>- loan of model to NASA</td>
<td>Free</td>
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<tr>
<td></td>
<td>- LES R&amp;D</td>
<td>LDRD</td>
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<td></td>
<td>- computational resources</td>
<td>ASCI</td>
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<td>USC</td>
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<td>Caltech</td>
<td>- LES model development</td>
<td>ASCI, DOD</td>
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<td>- computational resources</td>
<td>ASCI, NSF, DOD</td>
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<td>NASA Ames</td>
<td>- 7’x10’ wind tunnel tests</td>
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<td></td>
<td>- 12’ wind tunnel tests</td>
<td>1/3 Cost</td>
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<td></td>
<td>- loan of Navistar’s model</td>
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<td>LLNL</td>
<td>- computational resources</td>
<td>ASCI</td>
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<td></td>
<td>- LES and code development</td>
<td>ASCI/LDRD</td>
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The projected milestones are segregated into benchmark cases with advancing levels of complexity.

Projected milestones for first four years of project (FY98 through FY01)

<table>
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<tr>
<th>Task</th>
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<td>Workshop II</td>
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<tr>
<td>MYPP with projected budget and milestones</td>
<td>5/98</td>
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<tr>
<td>Continued site visits</td>
<td>12/98, 12/99, 12/00</td>
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<td>Level 1 Benchmarks: Establish generic shapes and outline test cases for investigation of trailer-tractor height and gap mismatch (Demo)</td>
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<td>Test data at moderate Re for Level 1 benchmarks (Demo)</td>
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<td>RANS, LES/FEM, LES/Vortex computations of Level 1 benchmarks at moderate Re (DEMO)</td>
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<td>Workshop III: Possible computation contest</td>
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<td>Level 2 Benchmarks: Establish generic shapes</td>
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<tr>
<td>Test data at moderate and high Re for Level 2 benchmarks</td>
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Particle traces, Re = 1.6×10^6
Ground Transportation System (GTS) vehicle

Texas A&M 7’x10’ low speed tunnel test

Test condition:

Run = 31, $Re = 1.6 \times 10^6$, Wheels removed

Yaw angle = 0 (deg.)

Free stream velocity = 78 (m/s)

Density = 1.17 (kg/m$^3$)

Static pressure = 99,470.6 (Pa)

Kinematic viscosity = $1.555 \times 10^{-5}$ (m$^2$/s)
History
- Primarily high speed flow simulations
- Recently, there is an effort in low speed flow simulations

Advanced Computational Capabilities
- SACCARA (Sandia Advanced Code for Compressible Aerothermodynamics Research and Analysis)
- CFD-ACE (Navier-Stokes code)
- CHAD (Navier-Stokes code)
- NS3D (Navier-Stokes code)
- SPRINT (PNS code)
- SANDIAC (Euler code)
- MGAERO (Euler code)
- HIBLARG (Boundary layer code)
Code Development & Numerical Simulation

- Physics Enhancement through Internal Research Programs
  - ESRF/LDRD
  - ESRF/Tech Base

- Range of Modeling and Simulation
  - Full Navier-Stokes code
    - Large Scale Computing (ASCI)
  - PNS codes
  - Euler Codes
  - Boundary Layer codes
SACCARA
Current Capabilities:

- Based on parallel version of INCA™ Full Navier-Stokes code
- Implicit, Multi-block, structured grids for 2-D, Axisymmetric, and 3-D flows
- Finite volume discretization (steady and unsteady flows)
- Subsonic --> Hypersonic flow fields
- Ideal, equilibrium, and thermo-chemical nonequilibrium finite-rate gas chemistry
- Zero-, one-, and two-equation turbulence
- MP implementation on a variety of distributed parallel architectures (IBM, Intel, etc.)
Improving Physical Models in SACCARA

- Methods to model transition
  - Engineering models based on boundary layer
  - Parabolized Stability Equations (PSE) approach

- Turbulence models
  - One-equation Spalart Allmaras model
  - New two-equation $k-\omega$ model
  - New two-equation $k-\zeta$ model
DOE Truck Aero Project

- History
  - SNL GTS Work (RAMPANT), LDRD
  - Ahmed-body flow simulation (CHAD), USCAR/SCAAP

- Currently working on
  - Gridding the SNL GTS model
  - Running flow simulations for the GTS model with SACCARA
Truck Aerodynamics:

Large-Eddy Simulation (LES) using the Finite-Element Method (FEM)

Rose McCallen, Ph.D.
Lawrence Livermore National Laboratory

October 1998
Large-eddy simulation provides a wealth of information and less empiricism.

Reynolds-Averaged Navier-Stokes (RANS)
   Many empirical parameters
   2D, steady, time-averaged solution

Backward-facing step: streamwise velocity

Large-eddy simulation (LES)
   One empirical parameter
   3D, unsteady solution of vortex shedding
What do advanced tools provide and what are the challenges in developing and using these tools?

Background

LES/FEM
R&D issues

Data analysis

Time-averaging, visualization, time histories, and power spectrum

Approach
Turbulent flow contains eddies ranging from large-scale to small-scale.

Large-eddy simulation captures the large-scale motion and approximates the small-scale motion.

all turbulent motions = large-scale motions + small-scale motions

= ‘resolved’ scale + ‘subgrid’ scale

\[ u_\alpha = \bar{u}_\alpha + u'_\alpha \]
LES/FEM provides a unique approach for solving practical problems.

Advantages of LES
Captures 3D time-dependent motion
Less empiricism than other methods

Advantages of FEM
Unstructured meshes
Natural boundary conditions
Coupling to other FEM codes

Zero natural boundary conditions capture the vortical outflow
The challenges are related to physical as well as computational modeling.

Boundary Conditions
No slip/slip, outflow/inflow, periodic

Size and Runtime
Resolution of small eddy motion, evolution over long time scales

Mesh Refinement
Adaptive, unstructured

Turbulence Models
Approximations to reduce problem size and runtimes

Analysis
Large data sets, visualization, convergence testing

Numerics
Appropriate scheme, parallelization, solvers
Time histories provide local flow information

Velocity in core of flow - transition from 2-D to 3-D

Velocity at points near wall

Comparison of gradients near wall
Power spectrum analysis can be used to determine the dominant frequencies.

Goal: Use power spectrum to compare runs
- different meshes
- different time steps

Issue: Peak identification
Flow visualization requires choosing the right parameters and movie making.

Pressure

Large-Eddy Simulation of vortex shedding in the wake of a bluff body.

Enstrophy
The first year deliverable is to integrate and develop the flow model and complete the demonstration problem.

Milestone | FY99 incompressible flow demonstration  
R&D | Solver integration/parallelization  
| Turbulence modeling  
| Boundary conditions  
| Data analysis  

Computational domain is chosen to minimize grid size:

- Slip with penetration (zero natural) on top and lateral boundaries
- Flow inlet with blockage correction
- No slip bottom boundary and truck walls
- Zero natural boundary condition at outflow
LES is a challenge but we have the experience and resources to succeed.

LES/FEM has advantages

Less empiricism

Built-in outflow conditions

Data analysis

Time-averaging, visualization, time histories, and power spectrum

Approach

Take advantage of existing methods and codes

Keep it simple - Smagorinsky SGS model and reduced computational domain
7x10 Test of the GTS Model

CFD Validation for Heavy Vehicle Drag
NASA Ames Research Center
October 22, 1998

Bruce Storms
7 x 10 Capabilities

Tunnel Speed $\leq$ 235 mph ($q \sim 140$ psf, $M=0.30$)

Test-section turbulence intensities:

$0.14\%, 0.30\%, 0.34\%$ (u,v,w) at $M=0.2$

Facility balance capacities:

Normal Force: 1800 lbs rt & lft, 800 lbs rear

Side Force: $\pm 2000$ front, $\pm 500$ rear

Axial Force: $\pm 500$ lbs ($\pm 1$ lb accuracy)

PSI system (surface pressures):

$\pm 0.1\%$ full scale accuracy
GTS Model: Ames 7x10 Installation

Scale: 1" = 1.75'
GTS Test Conditions

Tunnel Speed = 200 mph (q \sim 105 \text{ psf}, M=0.27)

Estimated drag (wind axis): \psi =0^\circ \quad \psi =14^\circ

\begin{align*}
q = 105 \text{ psf:} & \quad D = 41 \text{ lbs} \quad 120 \text{ lbs} \\
q = 80 \text{ psf:} & \quad D = 31 \text{ lbs} \quad 92 \text{ lbs}
\end{align*}

Yaw angle: -14^\circ < \psi < +14^\circ \text{ for forces & mom, pressures} \\
0^\circ, 5^\circ, \& 10^\circ \text{ for PSP} \\
0^\circ \& 10^\circ \text{ (or 5^\circ) for PIV}

Model configuration: Baseline, no wheels

Mounted 3 inches from tunnel floor
Flow Measurements

Particle Image Velocimetry

Accuracy: \( u = \pm 3.4\% \), \( v \& w = \pm 1.7\% \)

Time to acquire: \( \sim 10 \text{ min} / \text{condition} \) (1000 samples)

Pressure-Sensitive Paint

Accuracy: \( C_p \pm 0.03 \)

Acquisition time: \( \sim 30 \text{ min} / \text{condition} \)

Skin friction by Taos Hot-Film System

Separation, Reattachment, Transition detection

Oil Film Interferometry - Quantitative skin friction

Wall pressures, surface pressures, force & moments
Test Schedule

Test window: January 4 - 22, 1999 (3 weeks)

<table>
<thead>
<tr>
<th>Activity</th>
<th>shifts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installation / Check-out</td>
<td>2</td>
</tr>
<tr>
<td>Forces &amp; Pressures</td>
<td>1</td>
</tr>
<tr>
<td>Pressure-sensitive paint</td>
<td>4</td>
</tr>
<tr>
<td>Particle image velocimetry</td>
<td>7</td>
</tr>
<tr>
<td>Removal</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>15</strong></td>
</tr>
</tbody>
</table>
Issues

- Center of rotation closer to turntable centerline
- Tunnel speed significantly higher than previous test
- Second yaw angle: 5 or 10 deg??
- Wall pressures: yes/no ??
- PIV measurement stations ? >> parallel & perp. to freestream
- PSP on side and back only ? >> OK
- Skin friction measurement location ? >> TBD
- Oil film interferometry for quantitative skin friction ?
  >> on tunnel floor behind model
Heavy Vehicle Test in 7x10 at NASA Ames Research Center

PIV Overview

J.T. Heineck, PIV Task Manager
Experimental Physics Branch
NASA Ames Research Center
NASA Ames PIV Team - Capabilities

- Both 2D and 3D vectors for planar measurements
- 2% accuracy for instantaneous in-plane measurements, 4% for cross-plane. Time averaging improves statistical accuracy for steady flows.
- Images acquired and data processed on Windows NT system.
- CFD Grid Matching
- Team Experience in Wind Tunnel Testing
- Uses: Vortex Structure and Position, CFD Validation, Shear Layers, Jets, Flames
The PIV Method

- The seeded flow is illuminated with dual head pulsed Nd:YAG laser. Laser is optically shaped to form a sheet 1mm thick and spans the region of interest.
- Special high-resolution, dual-exposure digital camera(s) is (are) focused using high resolution lenses on the plane of the laser sheet.
- Timing of pulses are spaced in microseconds, the cameras are synchronized to the laser.
- Images taken are of individual particles in the area of interest.
- The image pair undergoes cross correlation using Fourier methods.
- The distance and direction the particle image shifts at grid points are determined.
- Vectors are calculated based on these shifts. The vector field is the resulting data.
PIV Issues for Tunnel Testing

- Identify the region of interest and flow structure
- Determine the data required e.g. 2D vs. 3D, axial and/or orthogonal to free stream, level of statistical accuracy for Reynolds averaged velocities.
- Laser is powerful, may damage the surface or paint of some models
- Consistency of seeding will effect efficiency of data collection and quality of data
- Calibration and focus procedures take approximately 1-2 hours for a laser sheet location change
- 2 days of set up, 2 people needed to operate system.
- Data acquisition takes approximately 10 minutes per condition after tunnel stabilizes.
Top View

GTS Model: Ames 7x10 Installation

Scale: 1' = 1.75'

Laser Sheet Position (est) introduced from top of tunnel, two orientations

Balance trench

1" Dia mounts

14 in

17 in

45.0 in

68.7 in

120 in

56.0 in

Air flow
Sample Vector Image