The Lattice-Boltzmann Method

An alternative for unsteady flow simulations

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Overview

- Exa Corporation Overview
- Lattice Boltzmann Method
- Aerospace Applications
- Challenges & Plans
Exa Corporation Overview

- Founded in 1992
  - Based on research at MIT
  - IPO in June 2012
  - Total investment in LBM technology > $200M

- Focus on vertical markets
  - Initial market: ground transportation
  - Built strong industrial partnerships

- Targeted expansion to Aerospace in past 5 years
Automotive Example
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Lattice Boltzmann Method

Microscopic
- Molecular Dynamics

Mesoscopic
- Discrete Particle Dynamics

Macroscopic
- Continuum Equation

Boltzmann Equation

Lattice Boltzmann

Navier-Stokes
LBM Key Characteristics

- Navier-Stokes physics are fully recovered
- Highly efficient unsteady flow solver
- Very low numerical dissipation
Comparison to higher-order NS Schemes

- Standing planar wave

LBM Key Characteristics

- Navier-Stokes physics are fully recovered
- Highly efficient unsteady flow solver
- Very low numerical dissipation
- Easy handling of very complex geometries
  - *Automatic generation of volume mesh*
  - *Nested cartesian mesh with multiple resolution level*
Process Flow Chart

CAD geometry

Surface mesh

Case setup (VR setup)

Automatic volume grid generation

Simulation

Post-processing

~6 hours

~3 hours

2 hours

16 hours on 512 cores

4 hours
PowerFLOW Mesh Structure
LBM Key Characteristics

- Navier-Stokes physics are fully recovered
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  - Automatic generation of volume mesh
  - Nested cartesian mesh with multiple resolution level
- Stability is a-priori guaranteed
- “LES-like“ turbulence model
  - Modified RNG model in regions of attached/steady flow
  - Switch to hyperviscosity-type LES model based on local swirl
  - Extended wall model
Tandem Cylinders
Instantaneous vorticity field

Experimental PIV (BART)

LBM

$\omega_z D/U_0$

Exa
LBM Key Characteristics

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  - Switch to hyperviscosity-type LES model based on local swirl
  - Extended wall model
- Current version limited to low speed
  - Update later in this presentation
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Acoustics – Airframe Noise - LG

LAGOON Benchmark by Exa Corporation
Surface probe pressure power spectral density, probe K15

PSD [dB/Hz]

Frequency [Hz]

Fine
Experimental C19
Experimental F2
Airframe Noise: Full Business Jet with deployed NLG

Sources
BANC-II Workshop
AIAA 2012-2235
BANC-II/PDCC-NLG: near-field results

![Graph showing PSD vs Frequency]

- PF (coarse res.)
- PF (medium res.)
- PF (fine res.)
- UFAFF meas.
- BART meas.

PSD (dB/Hz)

Frequency (Hz)
Towards Virtual Certification

GPS aircraft trajectory

PNL: Tone-smoothed measured signal - 0.1 s time window

Full on-ground noise signal
High-Lift Aerodynamics

- Full Geometry
- Simplified Geometry
Excellent agreement for lift in linear range

Lift detail at 28°: Excellent prediction for simulation with brackets (as in experiment)

Source: High-Lift Prediction Workshop (Chicago, 2010)
High-Lift Prediction Workshop: Comparison with other Codes

LBM predicts lift within experimental bounds (experiments performed with brackets)

Entries Numbers:
003, 14.01, 14.04: Overflow (NASA code, used by Boeing)
007: TAU (DLR code, used by Airbus)
009: PowerFLOW
010: Edge

Source: Overview Paper AIAA 2011-939
Active Flow Control

Natural flow

Actuated flow

Exa Corporation

Illinois Institute of Technology, Chicago, IL

California Institute of Technology, Pasadena, CA

Sources
AIAA 2010-4713
AIAA 2011-3440
Comparison PowerFLOW - Experiment

- Transient increase in lift $\Delta L$
  - *Only one cycle of actuation in simulation*
  - *About 60 cycles, phase-averaged in the experiment*

**Graph:**
- Experiment
- Simulation

- Good agreement overall
- Peak value and length of the transient lift well captured in simulation
Fan Noise

- Direct results from simulation
- Peaks captured at expected frequencies
- Broadband content levels in close agreement

Source
AIAA 2012-2287

NASA Experiment
PowerFLOW Simulation
Fan Noise: Band filtered results

- Filtered pressure on narrow bands
  
  Centered on $f_1$
  Filtered [470-490Hz]

  Centered on $f_3$
  Filtered [1420-1460Hz]

  - Strong diffraction patterns
  - Modal content more complex at 3rd BPF
Jet Noise (SMC000, Ma=0.35, New Setup)

vel_mag

Frame = 0000, Time = 0.00001 sec
Jet radiated noise

Flow (vorticity)

Far field Acoustics
ECS: Auxiliary Power Unit cooling

RANS MODEL

PowerFLOW MODEL
(no simplification required)

Preparation Time: 25 Days
Preparation Time: 2 Days

Temperature [degC]
50.0 80.0 110.0 140.0 170.0 200.0
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Aerospace Applications Wheel

- Aerodynamics
  - High-Lift Aerodynamics
  - Propulsion Aerodynamics
  - Cruise Aerodynamics
  - Wake Studies
  - Mission Aerodynamics
  - Buffeting
  - Water Ingestion
  - Icing
  - Flutter
  - Dynamic Loads
  - Static Loads
- Unsteady High-Speed Aerodynamics
- Rotating Geometry
- Moving Geometry & 6-DOF
- PowerFLOW
  - Transient Fluid Flow
  - Complex Geometry
  - Particle Dynamics
  - Dynamic FSI
  - Static FSI
- Loads
  - Dynamic FSI
  - Static FSI
  - Dynamic Loads
  - Static Loads
  - Icing
  - Water Ingestion
  - Buffeting
- Stability & Control
  - Helicopter Control Design
  - Control Surface Design
  - Aero Database Generation
- Aeroacoustics
  - Helicopter Noise
  - Fan Noise
  - Open Rotor Noise
  - Airframe Noise
  - Installation Noise
  - Jet Noise
  - HVAC/Duct Noise
  - Internal Aero Noise
  - Passenger Noise
  - Avionics Cooling
  - APU TM
  - Engine TM
  - Nacelle TM
  - Wheel TM
- ECS

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Extension of LBM to Higher Mach Numbers

D3Q19 Model (freestream $M_{\text{max}} \approx 0.4$)

D3Q39 Model (freestream $M_{\text{max}} \approx 3.0$)


Summary of Current PF Status

- Current technology limited to subsonic flow
  - Freestream Mach < 0.4 (local max Mach < 0.9)

- Prototype for High Mach number
  - Based on “fractional advection”
  - Limitations due to slow performance and higher numerical dissipation
  - Available today

- Full High Mach number version
  - Based on “direct advection”
  - Removes all limitations of fractional advection code
  - Development ongoing, Beta version planned this year
This study is named after the experimental results presented by Schardin [1]

Collision of a Planar Shock with a Finite Wedge

Mach_local distribution at a time before the planar shock reaches the finite wedge

Planar shock moves with Mach 1.34

Animation of the moving planar shock
Collision of a Planar Shock with a Finite Wedge
Collision of a Planar Shock with a Finite Wedge

Simulation

Experiment
Collision of a Planar Shock with a Finite Wedge

Comparision of triple point trajectory TP1 and TP2 and locus of vortex center V
Collision of a Planar Shock with a Finite Wedge

Density fields

PowerFLOW

Experiment
Collision of a Planar Shock with a Finite Wedge

Density distribution along the x-axis behind the wedge

Simulation $M_s=1.34$ (setup res256)
Setup

Model moved in y-direction
- 1 mm to -3 mm

Simulation Parameters:

- $L_{\text{ref}} = 0.18914 \text{ m}$
- $P_{\text{ref}} = 100000 \text{ Pa}$
- $A_{\text{ref}} = 0.13985 \text{ m}^2$
- $Rho_{\text{ref}} = 1.161 \text{ kg/m}^3$
- $Ma = 0.85$
- $Re = 5E+06$
- $T_{\text{ref}} = 300^{\circ} \text{ K}$
- $AOA = 0^{\circ}, 2^{\circ}, 3^{\circ}$
- Sim-Time = (55 to 144) * $L_{\text{ref}}$/Velocity_Inlet [Sec]

Windtunnel (NTF National Transonic Facility, NASA Langley) :
- CL = 0.5 at AOA (Angle of Attack) 3.02° with CD = 0.0275, CM = 0.0378

DPW-4 :
- CL = 0.5 at AOA (Angle of Attack) 2.34° with CD = 0.027, CM = -0.04025
Pressure distribution on the wing upper surface

AOA 2°

Simulation

Pressure-sensitive paint measurements
PowerFLOW Capabilities Today

Possible today
Not yet possible

Aerodynamics
- Unsteady High-Speed Aerodynamics
- Transient Fluid Flow
- Complex Geometry

Stability & Control
- Moving Geometry & 6-DOF

Aeroacoustics
- PowerFLOW
- Transient Fluid Flow
- Complex Geometry

Loads
- Wake Studies Aerodynamics
- Buffeting
- Water Ingestion
- Icing
- Flutter
- Dynamic Loads
- Static Loads
- Deicing System
- TM
- Nacelle
- Wheel
- APU

ECS
- Exhaust Gas
- Airframe Noise
- Installation Noise
- Jet Noise
- HVAC/Duct Noise
- Internal Aero Noise
- Passenger Noise
- Comfort Noise
- Avionics Cooling
Enabling Features

- **Moving geometry**
  - *Rotation available today*
  - *Arbitrary movement: 1-3 years*

- **Fluid-Structure Interaction**
  - *Static coupling: available today (prototype)*
  - *Dynamic coupling: 2-5 years*
Simulations of Full Aircraft

G550 - Model scale 20%
Ma=0.2, Re_{MAC}~3M
Aerodynamics case size ~200M cells
Acoustics case size ~2B cells

B747– Full Scale
Ma=0.2, Re_{MAC}~40M
Aero case size ~10B cells
Acoustic case size 50-100B cells
## Simulations of Full Aircraft

<table>
<thead>
<tr>
<th></th>
<th>Today (Business Jet)</th>
<th>Future Requirement (5 years) (Jumbo Jet)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Aerodynamic Case</strong></td>
<td>26 hours on 1000 cores (200M cells)</td>
<td>12 hours on ~27,000 cores (10B cells)</td>
</tr>
<tr>
<td><strong>Aeroacoustic Case</strong></td>
<td>165 hours on 2000 cores (2B cells)</td>
<td>12 hours on ~170,000 cores (50B cells)</td>
</tr>
</tbody>
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Adaptive Refinement

Automatic local refinement

Drag Coefficient

Lift Coefficient

Iteration

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Accuracy

- LBM offers high accuracy for unsteady & separated flows (including smooth surface separation)
  - *Now including supersonic flows*
- Open question: Is the use of a wall model limiting?

Speed

- LBM is a very efficient unsteady solver
- Full plane (aerodynamics) will be possible long before 2041

Robustness

- Key advantage of LBM