Recent Advances of the Lattice-Boltzmann Method for the Simulation of Transonic Flows

Swen Noelting

With contributions from: Hudong Chen, Raoyang Zhang, Pradeep Gopalakrishnan, Yanbing Li et al.
Ehab Fares, Damiano Casalino, Benedikt König, Benjamin Duda, André Ribeiro et al

Applied Modeling & Simulation (AMS) Seminar Series
May 10, 2016
Outline

- Motivation: CFD Applications in Aerospace
- Overview of PowerFLOW Projects at NASA
- Theory & Background
  - LBM
  - Turbulence model
  - Wall treatment
  - Extension to transonic flows
- Transonic Code Validation and Application Examples
  - Fundamental Validations
  - Industrial Application Examples
CFD Applications in Aerospace

- **CFD (RANS) well established**
  - Analysis at Design Point
  - Steady-State CFD

- **Limited Use of CFD**
  - Some off-design configurations
  - Limited unsteady CFD

- **No Productive Use of CFD**
  - Towards virtual certifications
  - Full flight envelope
  - LES (?)
Motivation – Vision 2030

- CFD Vision 2030
  - 2014 Report to NASA by Key Industry Players (Boeing, Lockheed, Pratt&Whitney,...)

- Main challenges for CFD to move beyond current status:
  - Efficient handling of unsteady turbulent flows with significant regions of separation
  - Mesh generation
  - Robustness and automation of CFD simulations
  - Efficient use of HPC infrastructure
  - Managing very large amounts of data
  - Multi-disciplinary analysis & optimization

- Hybrid RANS-LES and wall-modeled LES seen as best prospects

- Can LBM provide a contribution to address these challenges?
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Aeroacoustic Predictions
NASA ERA Project

- Simulation-based airframe noise predictions
  - Simulated geometry: As-built 18% scale Gulfstream model
  - Baseline configurations
    - 39° flap deflection, main gear removed
    - 39° flap deflection, main gear deployed
  - Most flap and gear concepts simulated prior to wind tunnel testing
    - ROLD, FENoRFins, FLEXSEL, etc.
    - Solid and porous versions of knee, wheel, brake fairings
  - Sample quiet configuration
    - FENoRFins plus fully treated main gear

- Accomplishments
  - Predicted farfield noise for baseline and quiet configurations in good agreement with14x22 measurements
    - Established computational simulations as an accurate predictive tool
    - Paved the way for application to full-scale
Airframe Noise – Flap Edge Noise

NASA ERA Project – G550

Time-averaged

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Airframe Noise – Flap Edge Noise

All simulations were carried out prior to wind tunnel tests.
Airframe Noise – Noise Reduction Concepts

Baseline

FLEXSEL

ROLD

FENoRFins
Computational Mesh

~2.6m half-span

~1mm hole size

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Baseline v. quiet Configurations

Flap 39º, main gear on configuration

Baseline Configuration (flap 39º, main gear on)

Treated Flap and Gear Configuration (flap 39º, main gear on)

Baseline Quiet
### Flap Noise Reduction Concepts

#### Experiment 14x22 WT

<table>
<thead>
<tr>
<th></th>
<th>FLEXSEL</th>
<th>ROLD*</th>
<th>FINS*</th>
</tr>
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<tbody>
<tr>
<td>OASPL (baseline – concept) [dB] (1kHz – 30kHz)</td>
<td>3.6</td>
<td>3.9</td>
<td>3.5</td>
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#### PowerFLOW Simulations

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*All simulations were carried out prior to wind tunnel tests*

*The aerodynamic values shown here correspond to the smallest holes and fin diameter tested*
Flow Control

Source
AIAA 2012-3239
Tail Rudder with Active Flow Control
Aerodynamic Simulation of Realistic 3D Ice Shapes

3D Ice Shapes provided by NASA/Glenn

Drag

Lift

Moment
3D Ice Shape – Surface Flow Visualization

Wind Tunnel Oil Flow

PowerFLOW Skin Friction Lines

reattachment
Fan Noise: RC2 Fan/OGV Configuration
Flow results between rotor & stator – comparison with NASA measurements

R = 100 % r_max

R = 80% r_max

R = 60% r_max
Far-field noise results

Measurements from:
Comparison of Far-Field Noise for Three Significantly Different Model Turbofans

Richard P. Woodward
NASA Glenn Research Center, Cleveland, Ohio 44135

Sideline emission angle (deg)

OASPL (dB)
High Speed Applications
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Boltzmann kinetic theory describes fluid behaviour based on particle density distribution function

\[ f(\bar{x}, \bar{c}, t) \]

particle number density at time t and position x with velocity \( \bar{c} \)

**Boltzmann Equation:**

\[
\frac{\partial}{\partial t} f(\bar{x}, \bar{c}, t) + \bar{c} \cdot \nabla f(\bar{x}, \bar{c}, t) = \Omega
\]

- LHS represents advections of particle distribution in space at fixed velocity for each \( \bar{c} \)
- RHS defined the collision process that involves inter-particle interactions
- Collision process can be modeled as simple relaxation to its equilibrium state (e.g. the BGK form*)
Lattice Boltzmann Methods

Discretization in space and time, using a finite set of discrete particle velocity values to represent the hydrodynamic properties:

Lattice Boltzmann Equation:

\[ f_i(\vec{x} + \vec{c}_i, t + 1) - f_i(\vec{x}, t) = \Omega_i(\vec{x}, t) \]

BGK form of collision:

\[ \Omega_i(\vec{x}, t) = -\frac{1}{\tau} \left[ f_i(\vec{x}, t) - f_i^{eq}(\vec{x}, t) \right] \]

Lower order LBE model recovers the Navier-Stokes equation at the nearly incompressible limit**

*Chen & Doolen 1998, **Qian et al. 1992., Chen et al 92
Macroscopic quantities are direct results of the moments of particle density distributions

- **Density** \( \rho(\vec{x}, t) = \sum_{i} f_i(\vec{x}, t) \)
- **Velocity** \( \rho(\vec{x}, t)\vec{u}(\vec{x}, t) = \sum_{i} \vec{c}_i f_i(\vec{x}, t) \)
- ...

Pressure obeys the thermally perfect gas law

\[
P = \rho \theta \quad \theta = RT
\]
No-slip/freeslip BCs are achieved via bounce-back/specular-reflection process*

![Diagram of bounce-back and specular reflection](image)

Momentum flux across the fluid-solid interface corresponds to surface pressure and wall shear stress*

\[
\mathbf{F} = p\hat{n} + \tau_w \hat{t} \sim \sum_{m \in \text{Pgrams, out}} \left( \mathbf{c}_m f_m \right)^\text{out} - \sum_{n \in \text{Pgrams, in}} \left( \mathbf{c}_n f_n \right)^\text{in}
\]

Generalized slip algorithm has been formulated to realize turbulence wall boundary conditions (slip velocity with imposed wall frictions)
Remarks

- Properly constructed LBE models can recover N-S physics, ... and beyond!
- LBM is a very accurate solver with extremely low numerical dissipation
  - Convection is exact due to the limited discrete velocities
- Very efficient for performing time dependent flow simulations
- A very robust solver due to realizability, and stability condition is a priori guaranteed

Plus .... Special Features of LBM Implementation in PowerFLOW
- Near wall physics (surfel concept)
- LBM-VLES turbulence model
- Variable resolution
- Efficient parallel implementation
- Extension to supersonic speeds
LBM-VLES Turbulence Model

- LBM-VLES turbulence model concept
  - Single turbulence model for all flow conditions
  - Resolved turbulent structures are simulated directly, unresolved scales are modeled
  - Subgrid contributions are accounted for by an effective relaxation time scale

\[
 f_i(\bar{x} + \bar{c}_i \Delta t, t + \Delta t) - f_i(\bar{x}, t) = -\frac{1}{\tau} \left( f_i - f_i^{eq} \right)
 \]

\[
 F_i(\bar{x} + \bar{c}_i \Delta t, t + \Delta t) - F_i(\bar{x}, t) = -\frac{1}{\tau_{\text{effective}}} \left( F_i - F_i^{eq} \right)
 \]

- Modification of turbulent flow relaxation time
  - Derived from a systematic renormalization group (RNG) procedure

\[
 \tau_{\text{effective}} = \tau_0 + \tau_{\text{turb}}, \quad \tau_{\text{turb}} = C_{\mu} \frac{k^2}{\varepsilon T} \frac{1}{\sqrt{1 + \tilde{\eta}^2}}, \quad \tilde{\eta} = \psi(\eta_s, \eta_\Omega, \eta_h, \ldots)
 \]

  - where \( \tilde{\eta} \) is the time scale of mean flow (strain, swirl, buoyancy, ...)
  - Effectively reduces eddy-viscosity in regions of high vortical fluctuations (e.g. separated regions)
  - Conceptually similar to DDES & SAS

- LBM-VLES contains HOT to account for non-linearity of the Reynolds stress

---

Near Wall Physics in PowerFLOW

- **Surfel Concept**
  - *Arbitrary orientation & shape of elements*
  - *Near wall Sampling*
    - All needed weights pre-computed based on near wall volume elements
    - Ensure Conservation
  - **Momentum exchange**
    - Correspond to changes in pressure and friction
  - *Second Order Accuracy*
  - *Extended wall model for high Re#*
    - Including pressure gradient effects
Once surface grids and regions of refinement are defined, volume grid generation is fully automatic.
Efficient Parallel Implementation

<table>
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<tr>
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<th>Power-FLOW</th>
<th>CFL3D</th>
<th>CEDRE</th>
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<tbody>
<tr>
<td>Turb. Model</td>
<td>VLES</td>
<td>MDDES</td>
<td>ZDES</td>
</tr>
<tr>
<td>Number of Elements</td>
<td>123M</td>
<td>43M</td>
<td>61M</td>
</tr>
<tr>
<td>Number of Procs.</td>
<td>276</td>
<td>240</td>
<td>480</td>
</tr>
<tr>
<td>CPU-hrs for 1s</td>
<td>21,000</td>
<td>854,000</td>
<td>1,960,000</td>
</tr>
<tr>
<td>simulated time*</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Manoha (Onera), Caruelle (Airbus), AIAA-2015

Lagoon (BANC-III)

Velocity PSD

Farfield PSD

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Efficient Parallel Implementation

Stanford WMLES*
CPU-hrs: 17,000,000**

PowerFLOW***
CPU-hrs: 5,000**


** CPUh normalized for 1 flow pass and a span of 1 chord

*** Simulations executed in collaboration with NASA
Rigorous Theory based on Hermite Expansions  
(Shan et al, 1998, 2006)

- **Projection of LBM in Hermite Polynomials**
  - Expansion coefficients are the moments of distribution function
  - No assumption on small Ma# or constant Temperature

- **Truncate the expansion to certain order**

- **Represent solution in Velocity Space**
Extension of LBM to Transonic/High speed Flows

- High order multi-speed LBE models (D3Q27, D3Q39, D3Q125 ...)

- Hybrid approach to couple with thermal dynamics field

\[
\partial_t S + u_\alpha \partial_\alpha S = -\frac{1}{\rho \theta} \partial_\alpha q_\alpha + \frac{\Phi}{\rho \theta}, \quad S = c_v \ln \left( \frac{\theta}{\rho^{\gamma-1}} \right)
\]

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Transonic Code Validation & Application

**Fundamental Validations**
- CDV nozzle
- Shock over Wedge
- RAE 2822 Airfoil
- Transonic Bump
- CRM

**Industrial Applications**
- Fan Noise
- Flow Control
- Jet Noise
- Buffet
2D CDV Nozzle (DNS): Sub-sonic/Transonic/Supersonic Flow Conditions

- Converge-Diverge Nozzle configuration
- Compared with analytical 1D inviscid flow solution
- Simulated at low viscosity at various flow conditions
Collision of a Planar Shock with a Finite Wedge Setup

Shock Tube Setup

High Pressure

Low Pressure

Fixed Wall

Outlet

Finite Wedge

Initial Conditions:
P4/P1 = 4.0, T4/T1 = 1

Boundary Conditions:
No-slip walls
Outlet pressure P1
Re 50000

Grid Resolutions:
Coarse h/128
Medium h/256
Fine h/512
Collision of a Planar Shock with a Finite Wedge

Animation of the plane shock moving over the finite wedge (Animation time 0.001 s)

Planar shock moves at Mach 1.34
Collision of a Planar Shock with a Finite Wedge

$t = 91 \ \mu \text{sec}$

$t = 0$ corresponds to the instant, when the planar shock first collides with the finite wedge
Collision of a Planar Shock with a Finite Wedge

\[ t = 128 \, \mu \text{sec} \]

\[ t = 0 \text{ corresponds to the instant, when the planar shock first collides with the finite wedge} \]
Collision of a Planar Shock with a Finite Wedge

t = 0 corresponds to the instant, when the planar shock first collides with the finite wedge.

$t = 151 \mu \text{sec}$

**Experiment**
AOA (Angle of Attack) = -2°

L_ref = 1 m
Area_ref = 1 m^2

Uoo
T_ref

P_ref

L_ref

X

Y

AOA

Inlet

Constant Grid Distribution

Frictionless Walls

VR-Interface

7.2 * L_ref

3.6 * L_ref

Outlet

2D-Turbulent-Simulation
Moo = 1.4
Re = 3.24E+07

P_ref
Rho_ref = 1.161 kg/m^3
T_ref = 300° K
AOA = -2°

P_ref = 100000 Pa

Re = 3.24E+07

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Grid
Resolution 512 per chord (coarse)
Voxel-Size 1000/512 = 1.95 mm
Total Voxels 1.46 Mill.
Fine Equivalent Voxels 1.01 Mill.
Supersonic Diamond Airfoil

Pressure Distribution for Moo 1.4 and AOA -2

Compression waves

Expansion waves

\[
P/P_{oo} \quad [\cdot] \\
0.7 \quad 1.4
\]
Supersonic Diamond Airfoil

P/P_{oo} on the Upper- and Lowerside of the Diamond Airfoil at Moo 1.4 and AOA -2°

- Simulation Upperside (Medium Grid)
- Simulation Lowerside (Medium Grid)
- Analytic-Solution (Upperside)
- Analytic-Solution (Lowerside)
## Supersonic Diamond Airfoil

<table>
<thead>
<tr>
<th>Angle of Attack AOA °</th>
<th>-2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inflow Mach Number Moo</td>
<td>1.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Grid</th>
<th>Coarse</th>
<th>Medium</th>
<th>Fine</th>
<th>Analytic-Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lift Cl [-]</td>
<td>0.1471</td>
<td>0.1474</td>
<td>0.1463</td>
<td>0.1473</td>
</tr>
<tr>
<td>Drag Cd [-]</td>
<td>0.0165</td>
<td>0.0165</td>
<td>0.0165</td>
<td>0.0165</td>
</tr>
</tbody>
</table>

| Pressure Relation P1/Poo | 1.0502 | 1.0501 | 1.0502 | 1.0502 |
| Pressure Relation P2/Poo | 0.7821 | 0.7819 | 0.7820 | 0.7838 |
| Pressure Relation P3/Poo | 1.2823 | 1.2820 | 1.2821 | 1.2841 |
| Pressure Relation P4/Poo | 0.9551 | 0.9555 | 0.9530 | 0.9553 |

| Mach Number M1 | 1.3617 | 1.3637 | 1.3661 | 1.3650 |
| Mach Number M2 | 1.5616 | 1.5625 | 1.5652 | 1.5690 |
| Mach Number M3 | 1.2109 | 1.2165 | 1.2215 | 1.2152 |
| Mach Number M4 | 1.4241 | 1.4260 | 1.4267 | 1.4310 |

Resolution coarse = 512 per chord
Resolution medium = 768 per chord
Resolution fine = 1024 per chord
Axisymmetric Transonic Bump

- Part of NASA’s 40% challenge
- Includes shock-induced separation, widely-used dataset for many years, axi-symmetry removes 2D questions
- RANS typically overestimates separation bubble by 20-30%

Axisymmetric Transonic Bump

- Volume cut shows location and sharpness of shock
- Skin friction contours indicate flow separation
- Iso-surfaces of $\lambda_2$ highlight resolved turbulent fluctuations in wake
- Unsteady flow in separation after shock captured
- Improved prediction of separation length and skin friction compared to standard RANS
Transonic Flow over the RAE 2822 airfoil

<table>
<thead>
<tr>
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<th>Case 1</th>
<th>Case 6</th>
<th>Case 9</th>
<th>Case 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ma</td>
<td>0.676</td>
<td>0.729</td>
<td>0.73</td>
<td>0.75</td>
</tr>
<tr>
<td>AoA</td>
<td>1.8148</td>
<td>2.4508</td>
<td>2.6873</td>
<td>2.7147</td>
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<tr>
<td>Re</td>
<td>5.7</td>
<td>6.5</td>
<td>6.5</td>
<td>6.2</td>
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Case 1 no shock
Transonic Flow over the RAE 2822 airfoil

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<td>AoA [°]</td>
<td>1.8148</td>
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<td>2.6873</td>
<td>2.7147</td>
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<tr>
<td>Re [10^6]</td>
<td>5.7</td>
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Case 6 moderate shock
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# Transonic Flow over the RAE 2822 airfoil

A strong shock wave is observed in Case 10, indicating a very high level of turbulence and pressure change in the flow. The table below summarizes the Mach number (Ma), Angle of Attack (AoA), and Reynolds number (Re) for each case:

<table>
<thead>
<tr>
<th>Case</th>
<th>Ma [-]</th>
<th>AoA [°]</th>
<th>Re [10⁶]</th>
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Transonic Flow over the RAE 2822 airfoil

Case 10
coarse

<table>
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<tr>
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<th>Medium</th>
<th>Fine</th>
<th>X-fine</th>
<th>XX-fine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution (cells / chord)</td>
<td>592</td>
<td>888</td>
<td>1333</td>
<td>2000</td>
<td>3000</td>
</tr>
<tr>
<td>Voxels ([10^3])</td>
<td>63</td>
<td>138</td>
<td>300</td>
<td>667</td>
<td>1500</td>
</tr>
<tr>
<td>CPUh</td>
<td>30</td>
<td>65</td>
<td>160</td>
<td>480</td>
<td>1880</td>
</tr>
<tr>
<td>Wallclock on 32 cores [h]</td>
<td>1</td>
<td>2</td>
<td>5</td>
<td>15</td>
<td>36</td>
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## Case 10

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<table>
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<tr>
<th>Resolution (cells / chord)</th>
<th>coarse</th>
<th>Medium</th>
<th>Fine</th>
<th>X-fine</th>
<th>XX-fine</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>592</td>
<td>888</td>
<td>1333</td>
<td>2000</td>
<td>3000</td>
</tr>
<tr>
<td>Voxels [10^3]</td>
<td>63</td>
<td>138</td>
<td>300</td>
<td>667</td>
<td>1500</td>
</tr>
<tr>
<td>CPUh</td>
<td>30</td>
<td>65</td>
<td>160</td>
<td>480</td>
<td>1880</td>
</tr>
<tr>
<td>Wallclock on 32 cores [h]</td>
<td>1</td>
<td>2</td>
<td>5</td>
<td>15</td>
<td>36</td>
</tr>
</tbody>
</table>
Transonic Flow over the RAE 2822 airfoil

<table>
<thead>
<tr>
<th>Case</th>
<th>Ma [-]</th>
<th>AoA [°]</th>
<th>Re [10^6]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>0.676</td>
<td>1.8148</td>
<td>5.7</td>
</tr>
<tr>
<td>Case 6</td>
<td>0.729</td>
<td>2.4508</td>
<td>6.5</td>
</tr>
<tr>
<td>Case 9</td>
<td>0.73</td>
<td>2.6873</td>
<td>6.5</td>
</tr>
<tr>
<td>Case 10</td>
<td>0.75</td>
<td>2.7147</td>
<td>6.2</td>
</tr>
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Transonic Flow over the RAE 2822 airfoil

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<td>2.7147</td>
</tr>
<tr>
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<td>6.5</td>
<td>6.5</td>
<td>6.2</td>
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<tr>
<td>Re [10^6]</td>
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<td>6.5</td>
<td>6.2</td>
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</table>
Transonic Flow over the RAE 2822 airfoil

Shock-induced separation expected to be better captured in 3D

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</tr>
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<td>Re [10^6]</td>
<td>5.7</td>
<td>6.5</td>
<td>6.5</td>
<td>6.2</td>
</tr>
</tbody>
</table>
3D Onera-M6

Span, $b$ 1.1963 meters
Mean Aerodynamic Chord, $c$ 0.64607 meters
Aspect Ratio 3.8
Taper Ratio 0.562
Leading-edge Sweep 30.0 degrees
Trailing-edge Sweep 15.8 degrees

<table>
<thead>
<tr>
<th>Mach #</th>
<th>Reynolds #</th>
<th>AoA</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.84</td>
<td>11.72E6</td>
<td>3.06</td>
</tr>
</tbody>
</table>

Geometry

<table>
<thead>
<tr>
<th>AR</th>
<th>3.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b$</td>
<td>1.196 m</td>
</tr>
<tr>
<td>$\Lambda_{LE}$</td>
<td>30°</td>
</tr>
<tr>
<td>$\Lambda_{TE}$</td>
<td>15.8°</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>0.562</td>
</tr>
<tr>
<td>$\tau$</td>
<td>0.646 m</td>
</tr>
<tr>
<td>$S$</td>
<td>1.506 m²</td>
</tr>
</tbody>
</table>
Flow-field Images

Mach

T/To

P/Po

rho/rho0
3D Onera-M6
Sectional Cp on Surface
NASA-CRM Model

- DPW4 Geometry
  - Reference CFD Data
  - Wing-body & tail
    - Supercritical wing
    - Built to the design-shape
    - Twist correction information available

- Measured at several Windtunnels
  - ETW, NTF, NASA Ames 11ft, JAXA JTWT
Wing Twist Correction

![Graph showing twist correction with baseline and twist corrected data.]

**PowerDELTA® morphing**
Simulated Geometry

ETW blade sting support including rounding
Computational Mesh*

<table>
<thead>
<tr>
<th></th>
<th>Coarse</th>
<th>Medium</th>
<th>Fine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution (cells / MAC)</td>
<td>683</td>
<td>1024</td>
<td>1536</td>
</tr>
<tr>
<td>Voxels [10^6]</td>
<td>30</td>
<td>88</td>
<td>274</td>
</tr>
<tr>
<td>CPUh [10^3]</td>
<td>5.4</td>
<td>17</td>
<td>38</td>
</tr>
<tr>
<td>Wallclock on 360 cores [d]</td>
<td>0.6</td>
<td>2</td>
<td>4.4</td>
</tr>
</tbody>
</table>

* Simulated with Symmetry
* additional resolution to resolve sting negligible
Results

Results

- DPW4 Geometry (NASA CRM model)

Results

- DPW4 Geometry (NASA CRM model)

Results – Wing Twist and Sting Effects

M=0.85  
Re=5×10⁶
Results – Wing Twist and Sting Effects

- DPW4 Geometry (NASA CRM model)

M=0.85  Re=5×10^6
Results – Wing Twist and Sting Effects

M=0.85  
Re=5\times10^6  
\alpha=2.9^\circ
Transonic Code Validation & Application

Fundamental Validations

- CDV nozzle
- Shock over Wedge
- RAE 2822 Airfoil
- Transonic Bump
- CRM

Industrial Applications

- Fan Noise
- Flow Control
- Jet Noise
- Buffet
• Full Span Flap (FSF) Configuration
• Re = 4.3 M
• Mach = 0.2
• Laminar to turbulence transition (LTT) included
TrapWing: Drag & Lift

Lift vs. AOA

Drag vs. AOA

Cl vs Cd

Moment vs AoA
Sectional Surface Pressure

LTT
Full-Turb

Locations of Pressure Taps (Config 1 - deployed)

Section 50
Surface Streamlines – AoA 32

LT

FullTurb

© Exa Corporation
NASA - Active Flow Control

Unactuated, Cmu=0.0

Actuated, Cmu=1.5%

C_p at 89% span

Exp. data (Cmu=0.0)
Exp. data (Cmu=1.0%)
Exp. data (Cmu=1.5%)
CFD (Cmu=0.0)
CFD (Cmu=1.0%)
CFD (Cmu=1.5%)

© Exa Corporation
Applications

- S&C Data
- Unsteady Loads
- Airframe Noise
- Control Surfaces & Spoilers
- Sting Correction
- Aero Loads Data (static)
- Propulsion Aerodynamics
- High Speed Wing Design
- Inlet Design
- Jet & Installation Noise
- Aft Body Design
- WT Corrections
- Icing
- Wing Body Fairing
- Nacelle Design
- Flow Control
- Ground Effect
- High-Lift Design
- Buffet Boundary
- Engine Integration
- Fan Noise
- Vortex Generators
Jet Noise: SMC000 (SP46): $Ma=0.9$, $T_j/T_o=2.7$

<table>
<thead>
<tr>
<th>$M_j = U_j/a_j$</th>
<th>$M_a = U_j/a_{inf}$</th>
<th>$T_j/T_{inf}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.548</td>
<td>0.90</td>
<td>2.70</td>
</tr>
</tbody>
</table>
3D SMC Jet, SP46: Centerline mean and RMS velocity

Mean velocity

RMS velocity
3D SMC Jet, SP46: Radical profiles of mean and RMS velocity

SMC000-sp46, profiles-vx at downstream locations from jet exit
Mj=0.5, Tj/To=2.7

Exp.
Reso-90
Reso-60
Reso-40

Exp. Consensus, Bridges Wemet 2010
• LBM-VLES (reso-90)
LBM-VLES (reso-40)
3D SMC Jet, SP46, FW-H OASPL and Far-field probes

\[ R = 100 \text{ D}_j \]

OASPL

![Graph showing SPL (dB) at 250 Hz and 2000 Hz vs. Observation angle (deg) for different angles of 90°, 135°, and 150°.]

Measurements (Brown, Bridges 2006)
- PowerFLOW (1-domain FW-H)
- PowerFLOW (2-domain FW-H)

© Exa Corporation
# Co-axial Nozzle case

<table>
<thead>
<tr>
<th>jet</th>
<th>M</th>
<th>Ma</th>
<th>Tr</th>
</tr>
</thead>
<tbody>
<tr>
<td>primary</td>
<td>0.87</td>
<td>1.41</td>
<td>2.65</td>
</tr>
<tr>
<td>secondary</td>
<td>0.90</td>
<td>0.90</td>
<td>1.0</td>
</tr>
</tbody>
</table>

---

Tinney & Jordan, JFM 611, 2008 – co-axial subsonic jets © Exa Corporation
Supersonic Jets (Work in Progress)
RC2 Case @12567 rpm

Density on rotor suction side
Flow analysis: slice @ r/R=0.8

Relative Mach number

Total Pressure

Mach [dimensionless]

Total Pressure [Pa]
Flow analysis: slice @ r/R=0.8

Density

Density Gradient

Density [kg/m^3]
0.700 0.852 1.005 1.157 1.309 1.500

grad_rho [kg/m^4]
0.00 20.00 40.00 60.00 80.00
Liner Simulation - Preview

- 1 DoF honeycomb liner
- Realistic orifice diameter, face sheet thickness and porosity (> 8000 orifices and honeycomb cells)
- Optimal design for BPF-2 and ~BPF-4
- Expected broadband properties because of slightly variable depth
Outlook: High-Speed Buffet
Buffeting study on OAT15A Supercritical Airfoil

- Shock wave- boundary layer interaction involving large scale instabilities.
- Preliminary 2D simulation at $M = 0.73$, angle of attack $= 3.5^\circ$, $Re \approx 3e6$

- Close agreement of average coefficient of pressure over the surface and amplitude of oscillation with experiments*.

Buffeting study on OAT15A Supercritical Airfoil (2D)

Frequency of oscillation (experiments): 78 Hz
Obtained frequency: 82 Hz
Summary

- Extension of LBM to transonic & supersonic flows
  - Achieved through hybrid higher-order LBM scheme
  - Enables simulations up to ~Mach 2.0
  - Preserves all key advantages of low speed LBM versions

- Main Initial Application Targets
  - Unsteady high-speed aerodynamics (buffet, ...)
  - Flow control
  - Propulsion noise: fan, jet & installation noise

- Status of LBM with regard to CFD Vision 2030 Report
  - Efficient handling of unsteady turbulent flows with significant regions of separation
  - Mesh generation
  - Robustness and automation of CFD simulations
  - Efficient use of HPC infrastructure
  - Managing very large amounts of data
  - Multi-disciplinary analysis & optimization
Thank You!