Lattice-Boltzmann Contribution the 2nd AIAA High Lift Prediction Workshop

David M. Holman
Ruddy Brionnaud

23th June 2013
Outline

• Motivation
• XFlow CFD code
  • Numerical approach
    • Relevant sample cases
• 2nd HiLiftPW results
  ▪ Case 1: Convergence analysis
  ▪ Case 2a: Low Reynolds number condition
  ▪ Case 2b: High Reynolds number condition
• Conclusions – Future work
Motivation

- Benchmark an accessible technology for **highly unsteady** flow simulation around **realistic aircraft** models
- **Assess** the XFlow ability to predict **stall** for **high-lift** landing or take-off configurations
Numerical approach

- Lattice Boltzmann Method (LBM)
  
  $\rightarrow$ Particle-based Lagrangian discretization
  $\rightarrow$ Mesoscopic scale

Particle-based

- Molecular
  - Direct Simulation Monte-Carlo

- Mesoscopic
  - Lattice-Boltzmann

- Macroscopic
  - SPH
  - VPM
**Numerical approach**

- **Lattice Boltzmann Method (LBM)**
  
  → Particle-based Lagrangian discretization
  → Mesoscopic scale
  → **Boltzmann transport equation:**

  \[
  \frac{Df}{Dt} = \Omega
  \]

  Distribution function
  \[
  f = f(x, v, t)
  \]

  **Density**
  \[
  \rho = \int f \, dv
  \]

  **Linear momentum**
  \[
  \rho u = \int fv \, dv
  \]

  **Navier Stokes**

  **Euler**
Numerical approach

- Lattice Boltzmann Method (LBM)
  - Particle-based Lagrangian discretization
  - Mesoscopic scale
  - Boltzmann transport equation:

\[
\frac{\partial f_i}{\partial t} + e_i \cdot \nabla f_i = \Omega_i
\]

- \(f_i\): particle distribution function in the direction \(i\),
- \(e_i\) the discrete velocity in the direction \(i\),
- \(\Omega_i\) the collision operator.
Numerical approach

- Lattice Boltzmann Method (LBM)
  
  → Particle-based Lagrangian discretization
  → Mesoscopic scale
  → Boltzmann transport equation:

\[ \frac{\partial f_i}{\partial t} + e_i \cdot \nabla f_i = \Omega_i \]

- Unique collision operator in central moment space.

\[ \Omega_i^{\text{MRT}} = M_{ij}^{-1} S_{ij} (m_i^{\text{eq}} - m_i) \]

- \( f_i \) : particle distribution function in the direction \( i \),
- \( e_i \) the discrete velocity in the direction \( i \),
- \( \Omega_i \) the collision operator.
Numerical approach

- Lattice Boltzmann Method (LBM)
  - Particle-based Lagrangian discretization
  - Mesoscopic scale
  - Boltzmann transport equation
  - Factorized Central Moment Lattice Boltzmann

\[
\mu_i x^k y^l z^m = \sum_{i}^{N} f_i e_{ix}^k e_{iy}^l e_{iz}^m
\]

\[
\tilde{\mu}_i x^k y^l z^m = \sum_{i}^{N} f_i (e_{ix} - u_x)^k (e_{iy} - u_y)^l (e_{iz} - u_z)^m
\]
Numerical approach

- **Lattice Boltzmann Method (LBM)**
  
  → Particle-based Lagrangian discretization  
  → Mesoscopic scale  
  → Boltzmann transport equation  
  → **Factorized Central Moment Lattice Boltzmann**

### Raw moments

\[
\mu_{x^k y^l z^m} = \sum_{i}^{N} f_i e_{ix}^k e_{iy}^l e_{iz}^m
\]

### Central moments

\[
\tilde{\mu}_{x^k y^l z^m} = \sum_{i}^{N} f_i (e_{ix} - u_x)^k (e_{iy} - u_y)^l (e_{iz} - u_z)^m
\]

- Stability issues at vanishing viscosity  
- Lower Mach number limit  
- Galilean invariance issues

- 4th order spatial discretization  
- Higher accuracy  
- Lower numerical dissipation  
- Positive effective viscosity  
- A-stable scheme
• Wall-Modeled Large Eddy Simulation (WMLES)
• Wall-Modeled Large Eddy Simulation (WMLES)

Turbulence modeling

Eddy size

DNS
Resolved

LES
Modeled
Resolved

VLES
Modeled
Resolved

RANS
Modeled

Wall-Adapting Local Eddy (WALE)
Turbulence modeling

- Wall-Modeled Large Eddie Simulation (WMLES)
  → Turbulent viscosity: Wall- Adapting Local Eddy (WALE) model

\[ \nu_t = \Delta_f^2 \frac{(G_{\alpha\beta} G_{\alpha\beta})^{3/2}}{(S_{\alpha\beta} S_{\alpha\beta})^{5/2} + (G_{\alpha\beta} G_{\alpha\beta})^{5/4}} \]

\[
\begin{align*}
S_{\alpha\beta} &= \frac{g_{\alpha\beta} + g_{\beta\alpha}}{2} \\
G_{\alpha\beta}^{\text{d}} &= \frac{1}{2} (g_{\alpha\beta}^2 + g_{\beta\alpha}^2) - \frac{1}{3} \delta_{\alpha\beta} g_{\gamma\gamma}^2 \\
g_{\alpha\beta} &= \frac{\partial u_{\alpha}}{\partial x_{\beta}}
\end{align*}
\]
Turbulence modeling

- Generalized law of the wall

\[
\frac{U}{U_c} = \frac{U_1 + U_2}{U_c} = \frac{u_T}{u_c} \frac{U_1}{u_T} + \frac{u_p}{u_c} \frac{U_2}{u_p} \\
= \frac{\tau_w}{\rho u_T^2 u_c} f_1 \left( y^+ u_T \right) + \frac{dp_w/dx}{|dp_w/dx|} \frac{u_p}{u_c} f_2 \left( y^+ u_p \right)
\]

\[y^+ = \frac{u_c y}{\nu}\]
\[u_c = u_T + u_p\]
\[u_T = \sqrt{\tau_w / \rho}\]
\[u_p = \left( \frac{\nu}{\rho} \left| \frac{dp_w}{dx} \right| \right)^{1/3}.
\]
Spatial discretization

- Lattice structure
  1. Complex Moving Boundaries
  2. Adaptative Refinement
Numerical approach

- Lattice Boltzmann Method (LBM)
  → Particle-based Lagrangian discretization
  → Mesoscopic scale

Turbulence modeling

- Wall-Modeled Large Eddie Simulation (WMLES)
  → Turbulent viscosity: Wall-Adapting Local Eddy (WALE) model

Spatial discretization

- Lattice structure
  → Moving boundaries
  → Complex and crossing geometries
  → Adaptative refinement
  → Curvature refinement
Outline

• Motivation

• **XFlow CFD code**
  • Numerical approach
  • Relevant sample cases

• 2\textsuperscript{nd} HiLiftPW results
  ▪ Case 1: Convergence analysis
  ▪ Case 2a: Low Reynolds number condition
  ▪ Case 2b: High Reynolds number condition

• Conclusions – Future work
D-JET Flight test manoeuvres

Dynamic simulation of flight test manoeuvres

The D-JET is a five-seat single engine aircraft currently in flight test phase in Canada.

A realistic analysis of the airplane manoeuvrability involves the presence of moving parts, such as the deflection of the elevators, the ailerons, or the elevons.

Different flight test manoeuvres simulated with XFlow are shown and compared against flight test data

• Pitch capture
• Dutch roll
• Stall
D-JET Flight test manoeuvres - Pitch

Trimmed conditions \rightarrow Pitching up 5° (for 1-2 s) \rightarrow Trimmed conditions \rightarrow Pitch oscillation & damping

VIRTUAL WIND TUNNEL

Rigid body dynamics:
- 1 DoF – Pitch rotation

Initial conditions:
- Flight data @ 0.7s.
D-JET Flight test manoeuvres - Pitch
D-JET Flight test manoeuvres – Dutch roll

Trimmed conditions → Rudder excitation → Back-and-forth rolling and yawing motion

VIRTUAL WIND TUNNEL

Rigid body – 3 DoF:
• Pitch rotation
• Yaw rotation
• Roll rotation

Initial conditions:
• Start time: 7.6 s
• Centered rudder
D-JET Flight test manoeuvres – Dutch roll
D-JET Flight test manoeuvres – Stall

Trimmed conditions

Stall: Pitch > 25º
Close elevator: Nose down

VIRTUAL WIND TUNNEL

Variable wind speed:

Elevator - Enforced movement:

Stall manoeuvre at maximum angle of attack

Angle of attack:

AOA - deg

0 5 10 15 20 25 30
35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55

2nd AIAA CFD High Lift Prediction Workshop (HiLiftPW-2)
1st HiLiftPW Special Sessions

Standard Lift and Drag analysis

**Preparation time**
5 minutes

**Computation time**
Longest run ~36 hours on two processors (8 cores) and 25 Million elements
1st HiLiftPW Special Sessions

Polar Sweep

- CAD geometry
- Simulation setup: ~5min
- Initial Lattice generation: ~2min
- Simulation: ~100h on a 12 cores (standard workstation), ~5-20 Million elements at 1.5s
- Post-processing: ~1h

Graph showing lift coefficient vs. angle of attack (α) with a range from 0 to 40 degrees.
Outline

• Motivation
• XFlow CFD code
  • Numerical approach
  • Relevant sample cases
• 2\textsuperscript{nd} HiLiftPW results
  ▪ Case 1: Convergence analysis
  ▪ Case 2a: Low Reynolds number condition
  ▪ Case 2b: High Reynolds number condition
• Conclusions – Future work
2<sup>nd</sup> HiLiftPW: Case 1

DLR-F11 wake structure
2nd HiLiftPW: Case 1

Convergence analysis

<table>
<thead>
<tr>
<th>Lattice resolution</th>
<th>Elements</th>
<th>Sim. time</th>
<th>Hardware</th>
<th>Run time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse = 2.5 mm</td>
<td>16,053,207</td>
<td>0.2 s</td>
<td>132 cores / 32GB RAM</td>
<td>6h</td>
</tr>
<tr>
<td>Medium = 1.25 mm</td>
<td>54,711,508</td>
<td>0.15 s</td>
<td>156 cores / 32GB RAM</td>
<td>24h</td>
</tr>
<tr>
<td>Fine = 0.9 mm</td>
<td>100,862,507</td>
<td>0.045 s</td>
<td>168 cores / 32GB RAM</td>
<td>19h</td>
</tr>
</tbody>
</table>

α = 7°
2<sup>nd</sup> HiLiftPW: Case 1

**Convergence analysis**

<table>
<thead>
<tr>
<th>Lattice resolution</th>
<th>Elements</th>
<th>Sim. time</th>
<th>Hardware</th>
<th>Run time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse</td>
<td>2.5 mm</td>
<td>16,735,791</td>
<td>0.41 s</td>
<td>120 cores / 32GB RAM</td>
</tr>
<tr>
<td>Medium</td>
<td>1.25 mm</td>
<td>56,985,885</td>
<td>0.375 s</td>
<td>168 cores / 32GB RAM</td>
</tr>
<tr>
<td>Fine</td>
<td>1.0 mm</td>
<td>87,417,402</td>
<td>0.095 s</td>
<td>192 cores / 32GB RAM</td>
</tr>
</tbody>
</table>

![Graph showing lift coefficient over time and number of lattice nodes](image)
Convergence analysis – Cp distribution - Main wing element @ P01

\( \alpha = 7^\circ \) \hspace{1cm} \( \alpha = 16^\circ \)

- Exp
- Coarse
- Medium
- Fine
Convergence analysis – Cp distribution - Main wing element @ P06

\[ \alpha = 7^\circ \]

\[ \alpha = 16^\circ \]
Convergence analysis – Cp distribution - Main wing element @ P11

$\alpha = 7^\circ$

$\alpha = 16^\circ$
Outlines

• Motivation
• XFlow CFD code
  • Numerical approach
  • Relevant sample cases
• 2nd HiLiftPW results
  ▪ Case 1: Convergence analysis
  ▪ Case 2a: Low Reynolds number condition
  ▪ Case 2b: High Reynolds number condition
• Conclusions – Future work
Low Reynolds number condition – Lift and Drag curves

**2\textsuperscript{nd} HiLiftPW: Case 2 (Re=1.35e6)**

**LIFT**

Lift Polar

- Lift coefficient vs Angle of attack [°]

**DRAG**

Drag Polar

- Drag coefficient vs Angle of attack [°]
Low Reynolds number – Cp distribution - Main wing element @ P01

α = 0°  
α = 7°  
α = 16°
Low Reynolds number – Cp distribution - Main wing element @ P04

\[ \alpha = 0^\circ \]

\[ \alpha = 7^\circ \]

\[ \alpha = 16^\circ \]
Low Reynolds number – Cp distribution - Main wing element @ P06

**α = 0°**

**α = 7°**

**α = 16°**
2nd HiLiftPW: Case 2 (Re=1.35e6)

Low Reynolds number – Cp distribution - Main wing element @ P08

\[ \alpha = 0^\circ \]  \hspace{1cm} \[ \alpha = 7^\circ \]  \hspace{1cm} \[ \alpha = 16^\circ \]
Low Reynolds number – Cp distribution - Main wing element @ P10

\(\alpha = 0^\circ\)

\(\alpha = 7^\circ\)

\(\alpha = 16^\circ\)
Low Reynolds number – Cp distribution - Main wing element @ P11

$\alpha = 0^\circ$

$\alpha = 7^\circ$

$\alpha = 16^\circ$
2nd HiLiftPW: Case 2 (Re=1.35e6)
2nd HiLiftPW: Case 2 (Re=1.35e6)
Outline

• Motivation
• XFlow CFD code
  • Numerical approach
  • Relevant sample cases
• 2nd HiLiftPW results
  ▪ Case 1: Convergence analysis
  ▪ Case 2a: Low Reynolds number condition
  ▪ Case 2b: High Reynolds number condition
• Conclusions – Future work
2nd HiLiftPW: Case 2 (Re=15.1 e6)

High Reynolds number condition – Lift and Drag curves

LIFT

Lift Polar

DRAG

Drag Polar

Angle of attack [°]

Lift coefficient

Drag coefficient

Exp

XFlow

Exp

XFlow
2nd HiLiftPW: Case 2 (Re=15.1 e6)

High Reynolds number – Cp distribution - Main wing element @ P01

\( \alpha = 0^\circ \)  \( \alpha = 7^\circ \)  \( \alpha = 18.5^\circ \)
High Reynolds number – Cp distribution - Main wing element @ P04

$\alpha = 0^\circ$  
$\alpha = 7^\circ$  
$\alpha = 16^\circ$
2nd HiLiftPW: Case 2 (Re=15.1 e6)

High Reynolds number – Cp distribution - Main wing element @ P06

\[ \alpha = 0^\circ \]
\[ \alpha = 7^\circ \]
\[ \alpha = 18.5^\circ \]
High Reynolds number – Cp distribution - Main wing element @ P08

\( \alpha = 0^\circ \)  \quad \alpha = 7^\circ \)  \quad \alpha = 16^\circ \)

Pressure distribution for 0\(^\circ\) at P08

Pressure distribution for 7\(^\circ\) at P08

Pressure distribution for 16\(^\circ\) at P08
High Reynolds number – Cp distribution - Main wing element @ P10

α = 0º

α = 7º

α = 16º

Pressure distribution for 0º at P10

Pressure distribution for 7º at P10

Pressure distribution for 16º at P10
High Reynolds number – Cp distribution - Main wing element @ P11

\( \alpha = 0^\circ \)  \hspace{1cm} \( \alpha = 7^\circ \)  \hspace{1cm} \( \alpha = 18.5^\circ \)
Outline

- Motivation
- XFlow CFD code
  - Numerical approach
  - Relevant sample cases
- 2nd HiLiftPW results
  - Case 1: Convergence analysis
  - Case 2a: Low Reynolds number condition
  - Case 2b: High Reynolds number condition
- Conclusions – Future work
Conclusions

• **Complex unsteady aerodynamics** simulations are conducted with XFlow in a straightforward way for different aircraft geometries, showing a good level of correlation with wind-tunnel data

• Results for the HiLiftPW-2 are in good agreement with experimental data

• The CFD setup is short and easy being the technology applicable even at early design stage
Future work

- Case 3 analysis
- Comparison against PIV data
- **AIAA Summer 2014 HiLiftPW-2 Special Sessions Paper**
Acknowledgements

David M. Holman
Ruddy Brionnaud
María García-Camprubí

Christopher Rumsey
David Levy

Luc Van Bavel
Thank you for your attention!

David M. Holman
david.holman@nextlimit.com

www.xflowcfd.com