The Actuator Line Model in Lattice Boltzmann Frameworks

Wake Characteristics and Turbulence Modelling

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MOTIVATION
Motivation

The Lattice Boltzmann Method is fast
Application in wind energy remains limited

11378 "Lattice Boltzmann"

172 "Lattice Boltzmann" & "LES"

11 "Lattice Boltzmann" & "Wind turbine"

Number of publications according to Web of Science (June 13, 2019)
SCOPE OF THIS STUDY
Scope of this Study

- Continuation of our recent Actuator Line Model (ALM) validation and analysis [1]

- Wake characteristics of a single turbine in uniform inflow

- Code-to-code comparison to standard finite volume Navier-Stokes (NS)
THE LATTICE BOLTZMANN METHOD
The fundamental variable of the LBM, the particle distribution function (PDF): $f(x, \xi, t)$

- Governing equation: The kinetic Boltzmann equation
The LBM

⇒ The Lattice Boltzmann equation:

\[ f_\alpha(x + e_\alpha \Delta t, t + \Delta t) - f_\alpha(x, t) = \Omega_\alpha \]  

D3Q19 lattice.

TikZ code by Christian Janssen.
The LBM

- Raw velocity moments of $f$ yield macroscopic quantities

$$\rho = \sum_{\alpha=1}^{m} f_{\alpha}, \quad \rho u = \sum_{\alpha=1}^{m} e_{\alpha} f_{\alpha}$$  \hspace{1cm} (2)

- A second-order approximation of the incompressible NSE
The Cumulant Collision Model

- $\Omega_\alpha$: Relaxation of $f$ in cumulant space

- Superior stability and accuracy at high Re

- AllOne ($\text{AO}$): $2^{nd}$-order in advection and diffusion [2]

- Parametrized cumulant ($\text{PC}$): $2^{nd}$-order in advection, $4^{th}$-order in diffusion [3]
CASE SET-UP
Case set-up

- ALM simulation of the NREL 5MW turbine in uniform laminar inflow
- $\lambda = 7.55$, $u_0 = 8 \text{ m/s}$
- Isotropic Gaussian smearing approach with $\epsilon = 2.5\Delta x$
- Smagorinsky model, $C_s = 0.1$
- The LB-solver ELBE [4]
- NS-FV reference: EllipSys3D [5, 6, 7]
RESULTS
Blade Loads

\[ \frac{F_t}{\rho u_0^2 R} \]

\[ \frac{F_n}{\rho u_0^2 R} \]

- **PC**
- **NS**
- **AO**
- **BEM**
First- and Second-order Statistics

- $\frac{r}{D}$
- $x/D$
- $u/u_0$
- $u' u'/u_0^2$
Power spectra

\[ E(f) \ [m^2/s] \]

\[ x/D = 12 \]

\[ x/D = 18 \]

\[ x/D = 24 \]

\[ f \ [Hz] \]

\[ 10^{-2} \ 10^{-1} \ 10^{0} \]

\[ 10^{-8} \ 10^{-6} \ 10^{-4} \ 10^{-2} \ 10^{-1} \ 10^{0} \]
Performance measures of ALM simulations in ELLIPSYS3D and ELBE with. Wall time and process time given per flow-through time (456s).

|                         | NS-FV                                      | Cumulant LBM                                |
|--------------------------|--------------------------------------------|---------------------------------------------|
| Processing unit          | 1080 CPU cores (Intel Xeon Gold 6130)       | 1 GPU (Nvidia RTX 2080 Ti)                  |
| Grid nodes               | 35 · 10^6                                   |                                             |
| CFL number               | 0.132                                      | 0.057                                       |
| Mach number              | -                                          | 0.1                                         |
| Wall time                | 2h 44m                                     | 0h 09m                                      |
| Process time [CPUh,GPUh] | 3019.79                                    | 0.14                                        |
| Real time / Comp. time   | 0.05                                       | 0.90                                        |
CONCLUSION
Conclusion

- The LB-ALM validation was successfully extended to the near- and far-wake

- The cumulant LBM is a suitable bulk scheme for typical high Re flows using relatively low spatial resolutions

- Notable differences between AllOne and parametrised cumulant

- Significant performance gains: close to real-time computing on the desktop
Outlook

- More soon in **Wind Energy Science**

- Mach-number dependency, more in-depth analysis of turbulence characteristics ...

- Long-term: Wind farm simulations with the LBM
Thank you! Questions?

[1] Asmuth H, Olivares-Espinosa H, Nilsson K and Ivanell S 2019 Journal of Physics: Conference Series
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[3] Geier M, Pasquali A and Schönherr M 2017 J. Comput. Phys. 348 862–888
[4] Janßen C F, Mierke D, Überrück M, Gralher S and Rung T 2015 Computation 3 354
[5] Michelsen J A 1994 Basis3D—a platform for development of multiblock PDE solvers Tech. Rep. Report AFM 92-05 Technical University of Denmark, DTU
[6] Michelsen J A 1994 Block structured multigrid solution of 2D and 3D elliptic PDE’s Tech. Rep. Report AFM 94-06 Technical University of Denmark, DTU
[7] Sørensen N N 1995 General purpose flow solver applied to flow over hills Ph.D. thesis Risø National Laboratory, Roskilde, Denmark