Dynamic Mode Decomposition analysis of flow fields from CFD Simulations

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Agenda

- Motivation
- DrivAer extension for Engine Bay Flow
- Lattice-Boltzmann based CFD for ground transportation
- Dynamic Mode Decomposition for unsteady automotive aerodynamics
Motivation

CFD for automotive applications...

- has complex and unsteady physics
- is most of the time computational very expensive
- needs high accuracy of predicted results
- has recently increased usage due to the virtualization of product development
- should have turn-around times as short as possible
Steady CFD is useful for the estimation of steady $C_D$ and $C_L$ values.

On the other hand, unsteady aerodynamics can greatly affect on running stability and ride comfort.

But, it is difficult to investigate in detail the flow structure causing unsteady aerodynamics by experiment. Unsteady CFD is highly demanded.
Dynamic Mode Decomposition
Motivation of DMD

• The flow field around a vehicle is very complex including various time and length scales
• Flow field computed by unsteady CFD also has enormous information

• It is still difficult to identify the coherent flow structure causing a target phenomenon from the result of CFD

It is believed that Dynamic Mode Decomposition (DMD) [1], [2] can extract coherent flow structure from complex flow field
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DrivAer extension for Engine Bay Flow

The known DrivAer Model

- Generic vehicle model that closes the gap between low detail geometries (academia) and production cars (industry)
- Three different rear end types and two different underbody types offer a variety of insights into external flow
- Very well accepted in the aerodynamic community
- **But:** Does not account for internal flow (no engine bay)

→ Demand for engine and engine bay geometry
DrivAer extension for Engine Bay Flow
New designed Engine bay

• New design of engine, gearbox, grilles, cooling air duct and two cooler packages (w/ & w/o leak around cooler)
DrivAer extension for Engine Bay Flow
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- Engine bay trim to ensure a defined flow region
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- Air exits into gearbox tunnel and front wheelhouses
DrivAer extension for Engine Bay Flow

New designed Engine bay

- New design of engine, gearbox, grilles, cooling air duct and two cooler packages (w/ & w/o leak around cooler)
- Engine bay trim to ensure a defined flow region
- Air exits into gearbox tunnel and front wheelhouses
- Level of detail fits the one of the DrivAer for external flow
- Changes to the original geometry are kept to a minimum

- Geometry will from now on be publicly available via the Institutes homepage www.drivaer.com
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Boltzmann equation is solved on a discrete lattice
- Underlying principle can be described as movement (streaming) and collision of particles on the lattice
- Streaming can take place at distinct speeds/directions according to the chosen model, e.g. D3Q19
- Time step according to CFL=1 with adequate sub-time stepping in refinement zones (octree-based 2:1 refinement)
- Macroscopic properties like density can be recovered from the moments of the distribution functions or from scale analysis
- LBM describes the Navier-Stokes equations with second order accuracy
• Lattice BGK equation (single relaxation time):

  • Collide:
    \[ f_i^C(x, t) = -\frac{f_i - f_i^{eq}}{\tau} \]

  • Stream:
    \[ f_i(x + e_i, t + 1) = f_i(x, t) + f_i^C(x, t) \]

• Equilibrium distribution (expansion valid for small Mach numbers; \( a, b, c, d \) depending on chosen type of lattice):

  \[ f_i^{eq} = \rho[a + be_i \cdot u + c(e_i \cdot u)^2 + du^2] \]

• Macroscopic moments:

  \[ \sum_i f_i^{eq} = \rho \quad \sum_i f_i^{eq} e_i = \rho u \]
• Lattice-Boltzmann Method (LBM) implemented on GPUs
• D3Q19-model for isothermal, unsteady 3D single-phase flows
• Turbulence modeling
  • $k-\omega$ SST (URANS)
  • Smagorinsky (LES)
• Integrated preprocessing with local grid refinement
  • Very fast generation of volume mesh within just a few minutes
  • Robust meshing algorithm can cope with, e.g., small surface defects, intersecting parts, etc.
• Case setup via Altair’s Virtual Wind Tunnel
• Three different setups investigated (Notchback):
  - Closed grilles (mock-up) – Baseline
  - Open grilles without leakage around the cooler
  - Open grilles with leakage around the cooler
• Post-Processing:
  - Integral values
  - Flow fields
  - Dynamic Mode Decomposition (DMD)
• Unsteady CFD using OpenFOAM® and ultraFluidX for simulation of 5s physical time
Numerical Simulations
Computational Resources

- OpenFOAM®: FV solver, unstructured but hexa-dominant grid
  - Element number: 66M cells
  - Turbulence model: DES
  - Hardware: 512 CPU cores (Sandy Bridge-EP Xeon E5-2680 8C)
  - Computation time: 40 hours

- ultraFluidX: LBM solver
  - Element number: 125M voxel
  - Turbulence model: LES (Smagorinsky)
  - Hardware: 4 GPUs (Nvidia K80)
  - Computation time: 29 hours
• Cooling drag of 10 counts without and 19 counts with leakage around the cooler
• Increased overall lift with engine bay flow
• Considerable changes in aerodynamic balance when considering engine bay flow but also between without and with leakage around the cooler
Change in aerodynamic balance between closed grilles (A) and open grilles (B, C) can be explained by the pressure distribution on the underbody (between front wheels, gearbox tunnel).

Higher front lift with leakage (C) around the cooler can be explained by the increased momentum towards the roof of the engine bay lining due to the leakage flow.
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Dynamic Mode Decomposition Theory - Decomposition

- DMD extract dynamic behavior of the flow described by $A$

\[ V_{2}^{N} = A V_{1}^{N-1} \]

DMD modes (Eigenvectors) : Spatial structure

Eigenvalues : Dynamic characteristics (Stability and Frequency)

$\Phi = \{ \phi_{1}, \phi_{2}, ..., \phi_{r} \}$

$\Lambda = \text{diag}(\lambda_{1}, \lambda_{2}, ..., \lambda_{r})$
The flow field can be reconstructed from DMD modes and its eigenvalues

\[ \mathbf{v}_i \approx \sum_{k=1}^{r} d_k \lambda_k^{i-1} \hat{\Phi}_k, \quad i = 1, \ldots, N - 1 \]

Scaling factor \( d_k \) are computed as follows, according to the above equation

\[ \mathbf{v}_1 \approx \sum_{k=1}^{r} d_k \hat{\Phi}_k = \hat{\Phi} \mathbf{d} \]

DMD modes can be scaled by scaling factor

\[ \phi_i = d_i \hat{\Phi}_i : \text{Scaled DMD modes} \]
Dynamic Mode Decomposition Processing module

- Reading of flow fields from ultraFluidX and OpenFOAM® possible
- If necessary, only subvolumes can be read in
- Two algorithms for the main DMD computation are available (SVD-based algorithm and Streaming-DMD algorithm)
- Output of Ensight Gold and .vtk files (plus diagrams for mode distribution)

**Reading of flow field from:**
- OpenFOAM®
- ultraFluidX

**If necessary, subvolume can be defined**

**Selection between:**
- SVD-based algorithm
- Streaming-DMD algorithm

**Output of modes in:**
- .vtk-format
- Ensight Gold Format

**Output of mode distribution as diagram**
Dynamic Mode Decomposition Processing module

- SVD-based algorithm:
  + very precise
  - big arrays are needed for the Singular Value Decomposition (high memory consumption), all snapshots are needed in advance
- Streaming-DMD algorithm:
  + memory consumption can be influenced by reducing the size of the POD-basis
  - loss of accuracy due to the POD-compression
- Performance:
  → SVD-based algorithm is a bit faster than Streaming-DMD,
    BUT all snapshots have to be calculated in advance
  → Streaming-DMD can be computed on the fly (in parallel to the CFD simulation)
Dynamic Mode Decomposition
Results – DMD on wall force vector

**Spectrum of mode amplitude**

\[ d_i = \sqrt{\sum_{k=1}^{M} (w_k \phi_{k,i})^2} \]

\[ \frac{d_i}{d_1} \]

**woL model**

Mode 2 \( \sim 3.5015 \text{Hz} \)

**wL model**

Mode 2 \( \sim 4.1258 \text{Hz} \)

※Normalized by amplitude of 1\(^{\text{st}}\) mode, respectively
Dynamic Mode Decomposition Results – DMD on wall force vector

Spatial distribution of scaled DMD modes $\phi_i$ - Z-direction

woL model … Mode 2 $\sim$ 3.5015Hz  

wL model … Mode 2 $\sim$ 4.1258Hz

Z-direction of DMD mode on wall force vector
Dynamic Mode Decomposition Results – DMD on wall force vector

Reconstructed Z-direction wall force from each DMD mode

woL model …
Mode 2 ~ 3.5015Hz

wL model …
Mode 2 ~ 4.1258Hz

Wall force Z [Pa]

Time: 1.255000

Time: 1.255000
The biggest fluctuating DMD mode (DMD mode 2) showed different fluctuation of z-direction force **behind the front wheels** between woL and wL model.

Reconstructed Z-force of woL case fluctuated with **same phase** between left and right.

z-force of wL case fluctuated with **antiphase** between left and right.
Thank you for your attention.

FOR MORE INFORMATION

VISIT www.drivaer.com
www.ultrafluidx.com