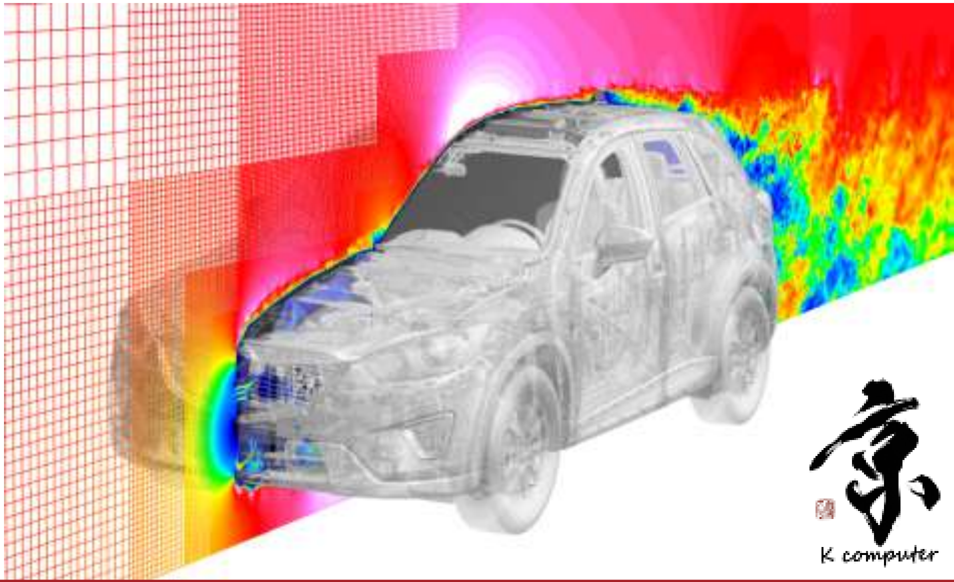
Computer simulations create the future

Application of HPC-CFD for Industrial Problems on the K Computer and toward Fugaku

Makoto TSUBOKURA

Team Leader of the Complex Phenomena Unified Simulation, RIKEN Center for Computational Science

Professor, Kobe University



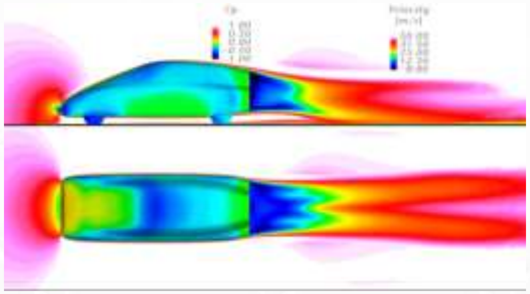
The 2nd R-CCS International Symposium

February 17th, 2020

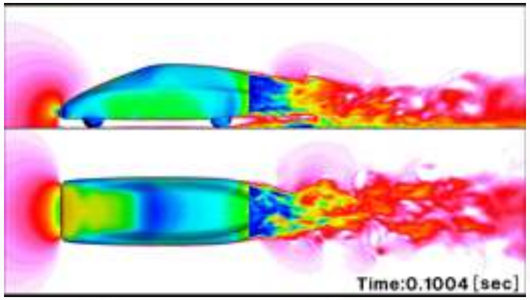
How HPC can change the industrial CFD?

- **High-resolution turbulence simulation**
  - *Higher time resolution realizing the unsteady simulation, capturing the transient phenomena.*

RANS



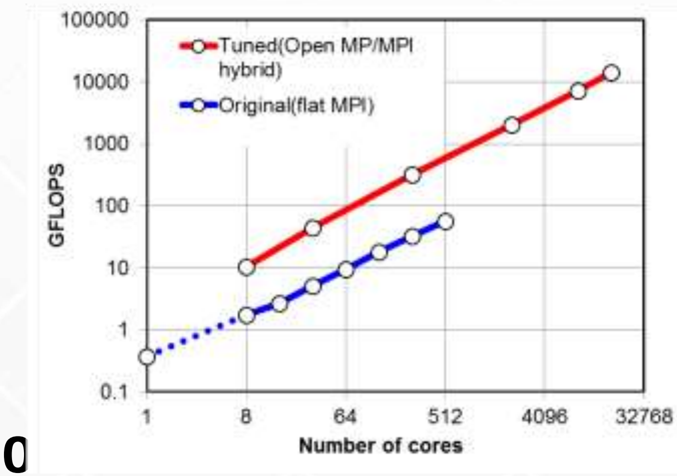
➡ LES



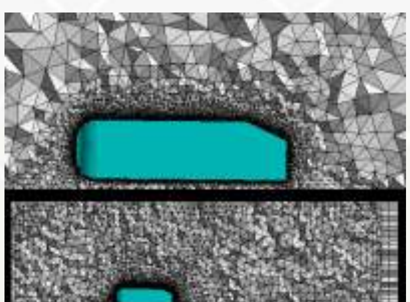
  - *Higher spatial resolution realizing the highly accurate simulation, independent on turbulence modeling.*
- **Coupled analysis realizing real-world simulation**
  - *Application of CFD to what conventional experiments are difficult to treat.*
  - *Coupling simulation of fluid motion with other physics such as structure deformation/vibration, heat and mass transfer, or aero-acoustics.*
- **Big data analysis**
  - *Optimization, Machine/Deep learning based on AI technique.*

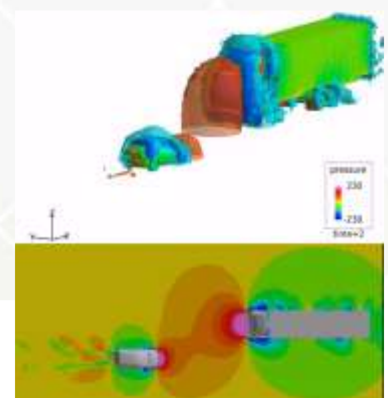
FrontFlow/red-HPC on the K computer

- **Unstructured Finite Volume Method.**
  - *Most popular and conventional data structure in industry.*
- **Hybrid OpenMP/MPI for HPC.**
- **Single node performance.**
  - *Thread parallelization by OpenMP.*
  - *9.5%/7.4% for hexa/tetra-hedral elements.*
- **Parallel efficiency.**
  - *Domain decomposition by application "METIS".*
  - *MPI among nodes.*
  - *96.5% parallelization efficiency (weak scaling).*



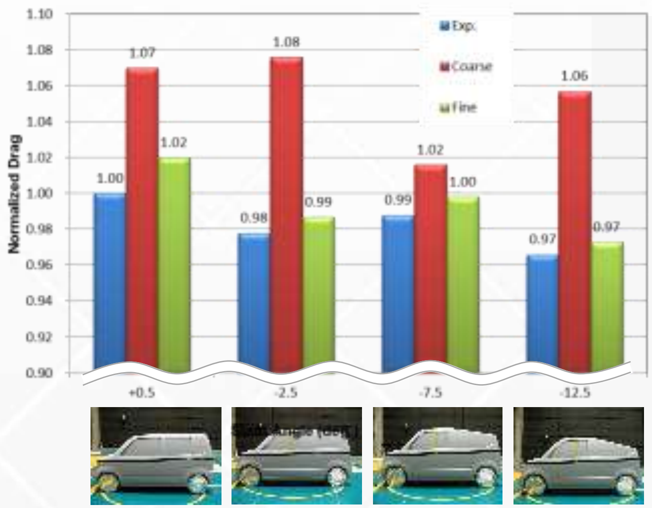
- **Up to 10 billion unstructured meshes on 10,0 nodes (80,000cores) on the K-computer .**
- **Various moving boundary methods including ALE.**

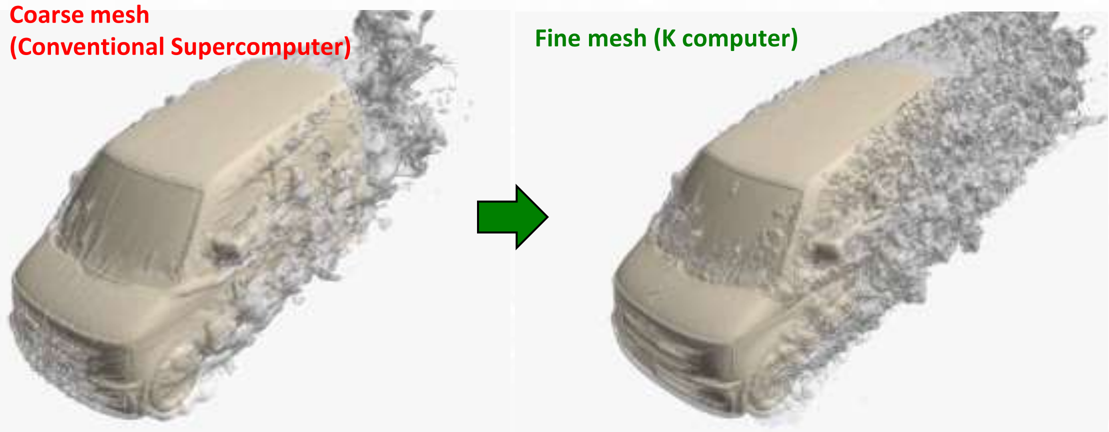


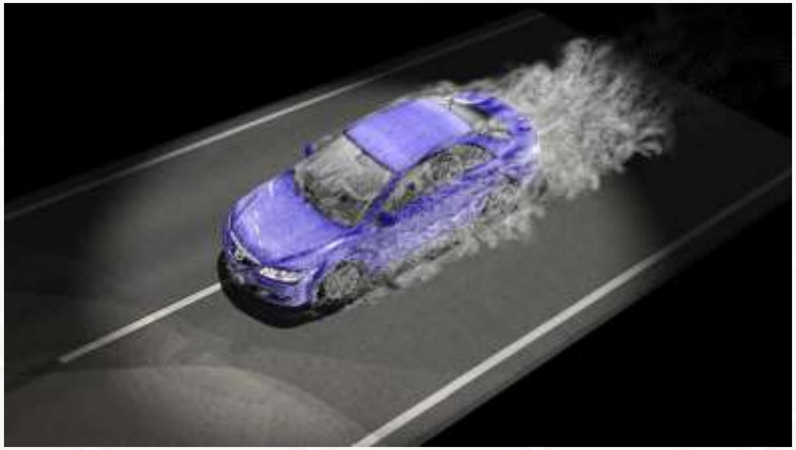


Success of the Unstructured CFD on the K Computer

- **Precise prediction of aerodynamic forces comparable to wind-tunnel measurements.**
  - The key is the surface resolution of less than 1mm.





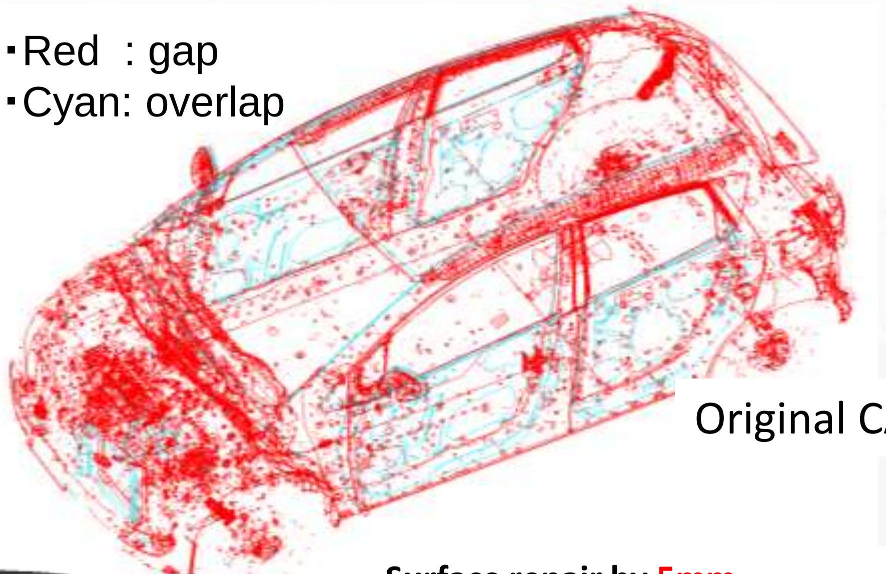


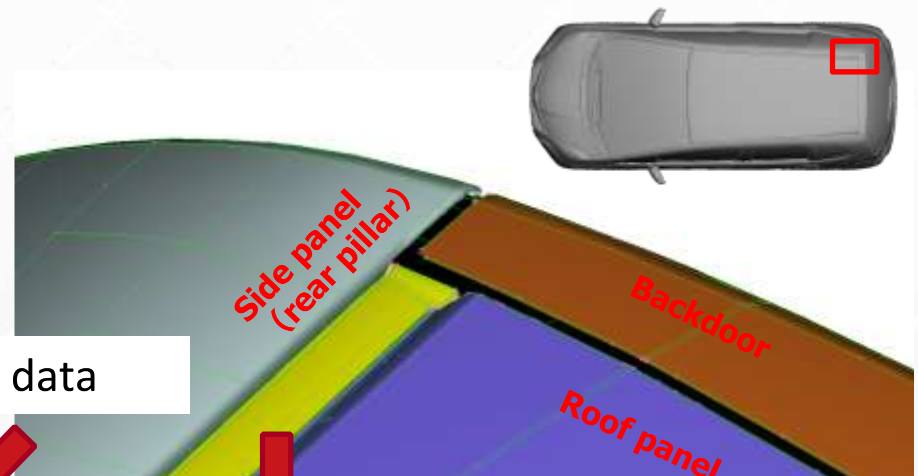
- **Real-World Aerodynamics Simulation.**
  - *Coupled with 6DoF vehicle motion and driver's reaction.*

- **Successful from the view point of academic research, but…**

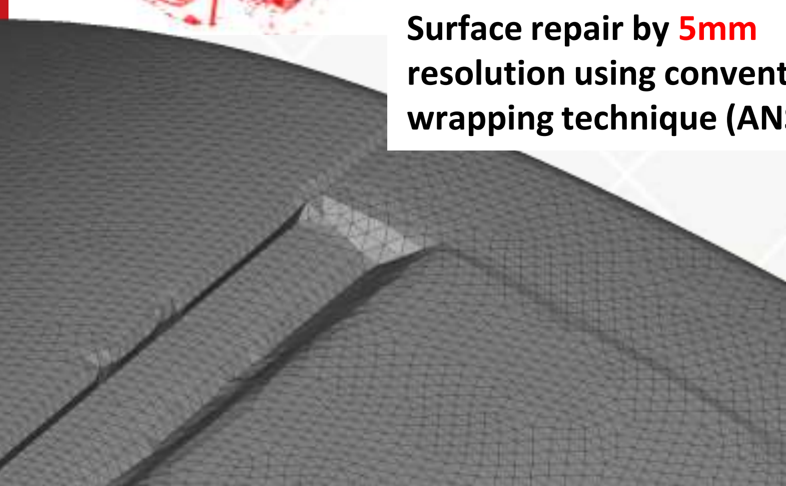
Surface Clean-up for Mesh Generation

- Industrial CAD is always very dirty…
- Higher resolution requires very long time for CAD clean-up.
- Resolution of less than 1mm surface is not realistic in industries.

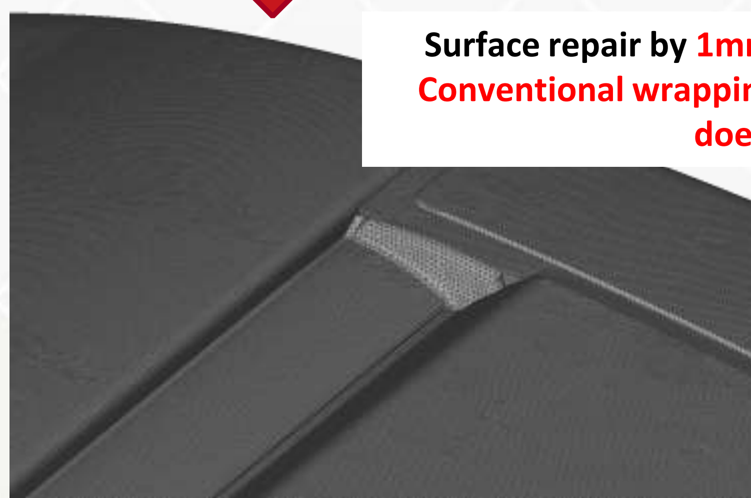




Original CAD data



Surface repair by 5mm resolution using conventional wrapping technique (ANSA(R))



Surface repair by 1mm resolution
Conventional wrapping technique does not work…

Numerical Methods

CUBE: Building Cube Method for Unified Simulation

- **Hierarchically structured Finite Volume Method**
  - *A solver for coupled phenomena: fluid/structure/acoustics/chemical reaction…*
  - *Building Cube Method for the unified data structure (Nakahashi et al., 2003)*
    - *Easy tune for both single node and parallel performance*
  - *Immersed Boundary Method (Fadlun et al., 2002)*

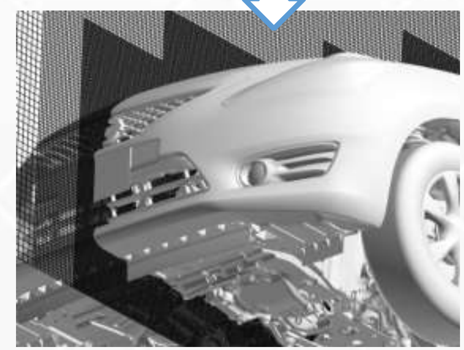
(1) Dirty CAD treatment (Onishi et al., 2013)

(2) Moving Boundary Method (Bale et al., 2016)

(3) Unified Compressible/Incompressible analysis (Li)

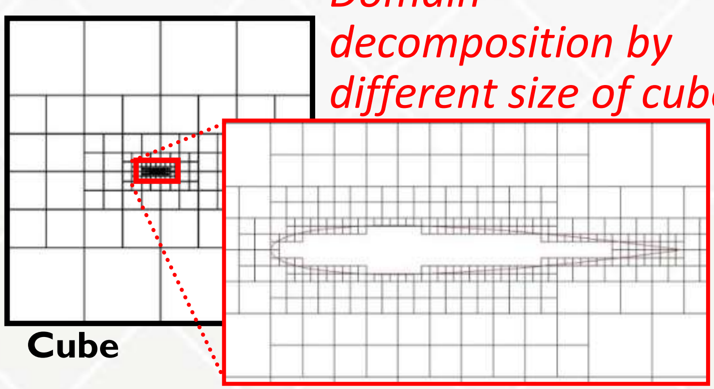
(4) Unified Fluid/Structure analysis (Nishiguchi)

Unstructured SAE 2014-01-0621



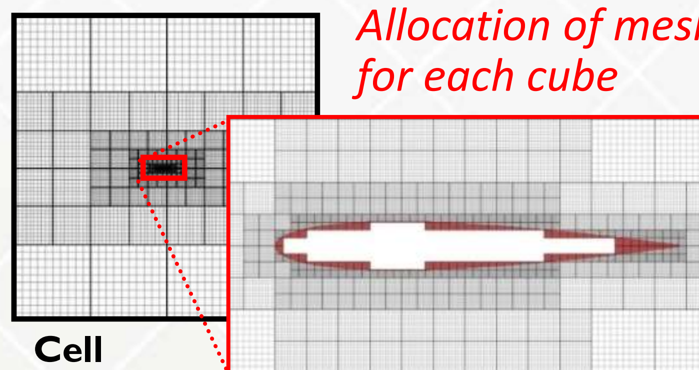
Structured(Cartesian) SAE 2014-01-0580

Domain decomposition by different size of cubes



Cube

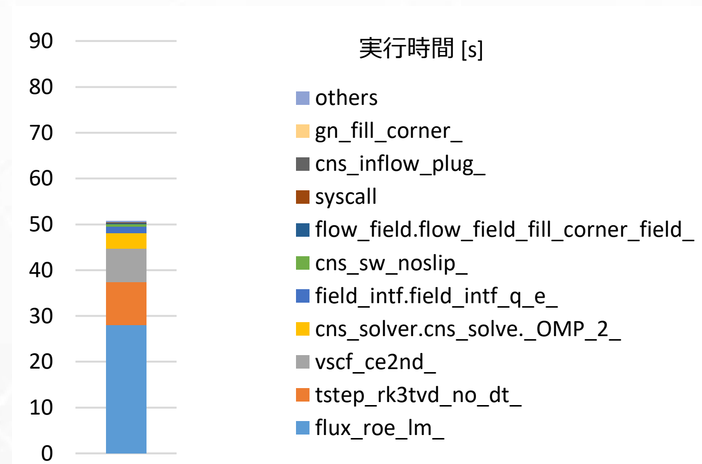
Allocation of meshes for each cube



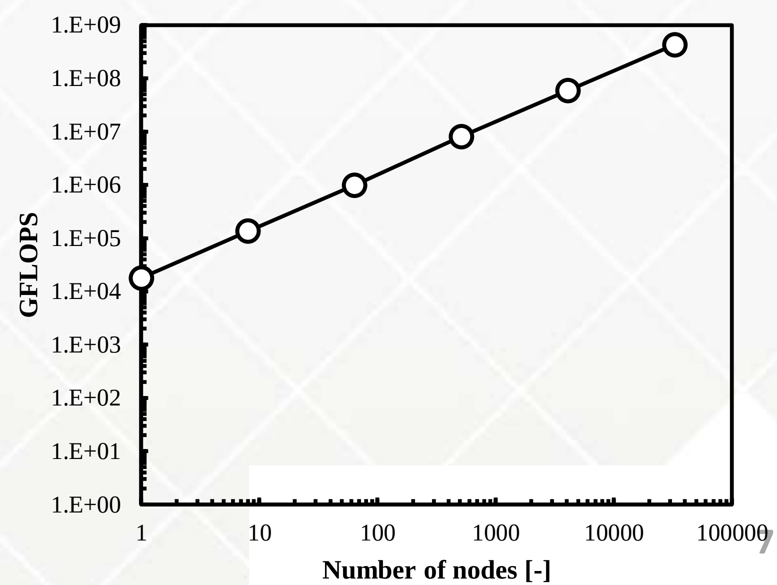
Cell

Performance on the K computer

- **Single node performance.**
  - *16×16×16 cells per cube.*
  - *23.7% on the K computer (8 threads).*
- **Parallel efficiency.**
  - *16 cubes per node.*
  - *Effective parallelization ratio: 99.99954%.*
  - *75.324899% parallel efficiency (weak scaling).*
    - Total nodes on the K computer
- **Expected to be 25 times faster on Fugaku**



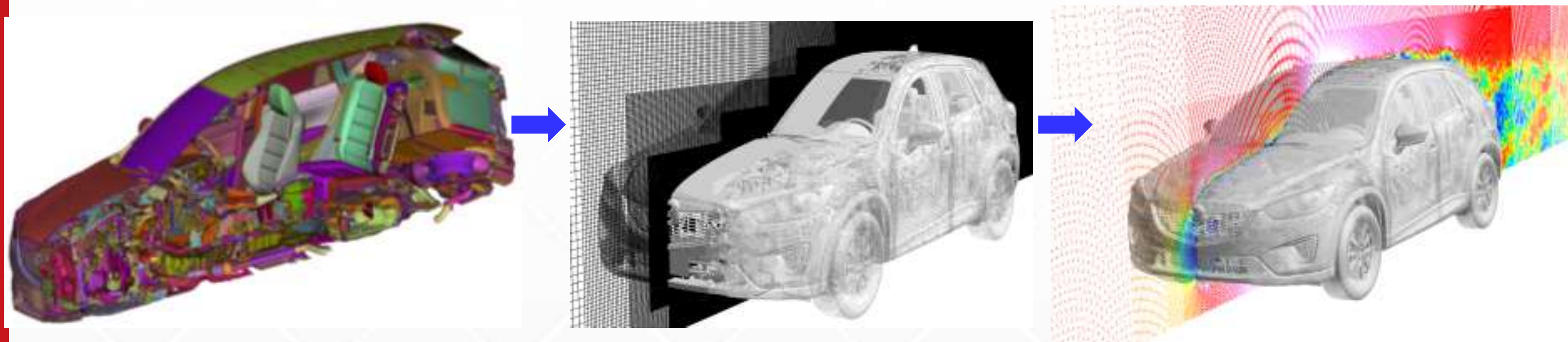
CUBE num.		Total cell num.	Node num.
4×4×4	64	262,144	1
8×8×8	512	2,097,152	8
16×16×16	4,096	16,777,216	64
32×32×32	32,768	134,217,728	512
64×64×64	262,144	1,073,741,824	4,096
128x128x128	2,097,152	8,589,934,592	32,768



Numerical Methods

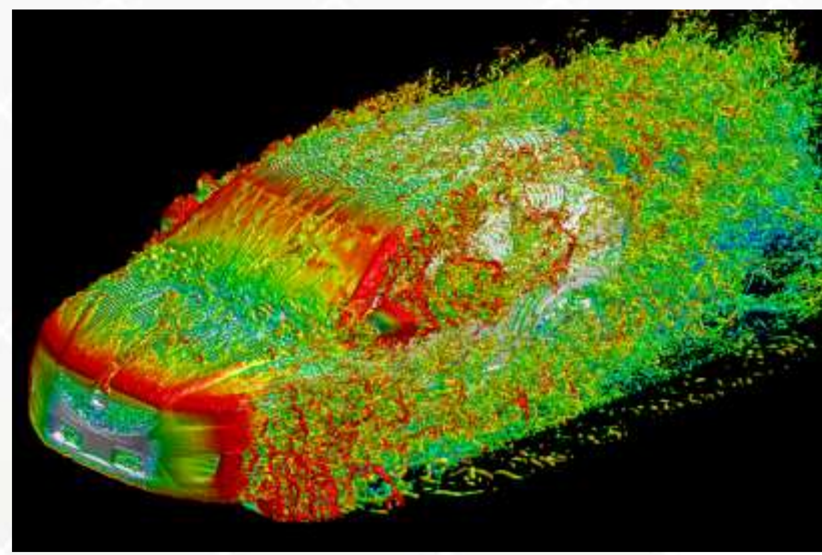
Full-scale vehicle aerodynamics simulation

- **World-largest full-scale vehicle simulation (27 billion meshes).**



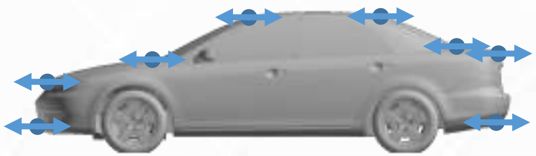
- *Maximum of 27 billion meshes with 0.7 mm resolution within 1 hour from the dirty CAD data.*

Condition	
Finest grid size	0.763 [mm]
Num. of cells	26,893,365,248
Grid generation time	About 20 min.
Pre-flow computational time (immersed boundary preparation)	About 30 min.
Delta t	1.0×10^{-6} [s]
Solution time	0.010 [s]
Parallel num.	273,576 cores (37,197 nodes)
Flow computation time	Several days

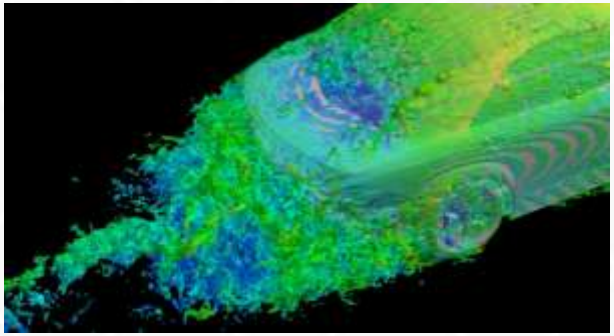


Multi-Objective Shape Optimization

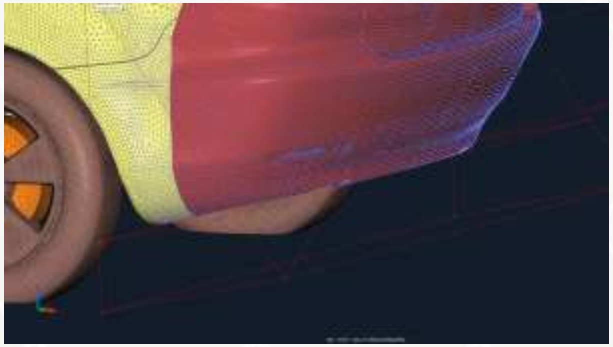
- **4 objectives (0° and -3° yaws)**
  - Drag and Lift at 0 yaw
  - Delta Drag (difference bet. 0 and -3)
  - Delta Lift (difference bet. 0 and -3)
  - Smaller is better for all four variables
- **8 design parameters**
- **Multi-objective Genetic Algorithm**
  - 18 models for each generation



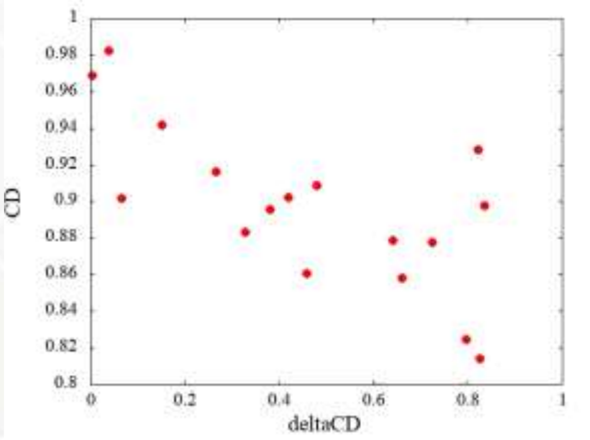
Geometry
STL format



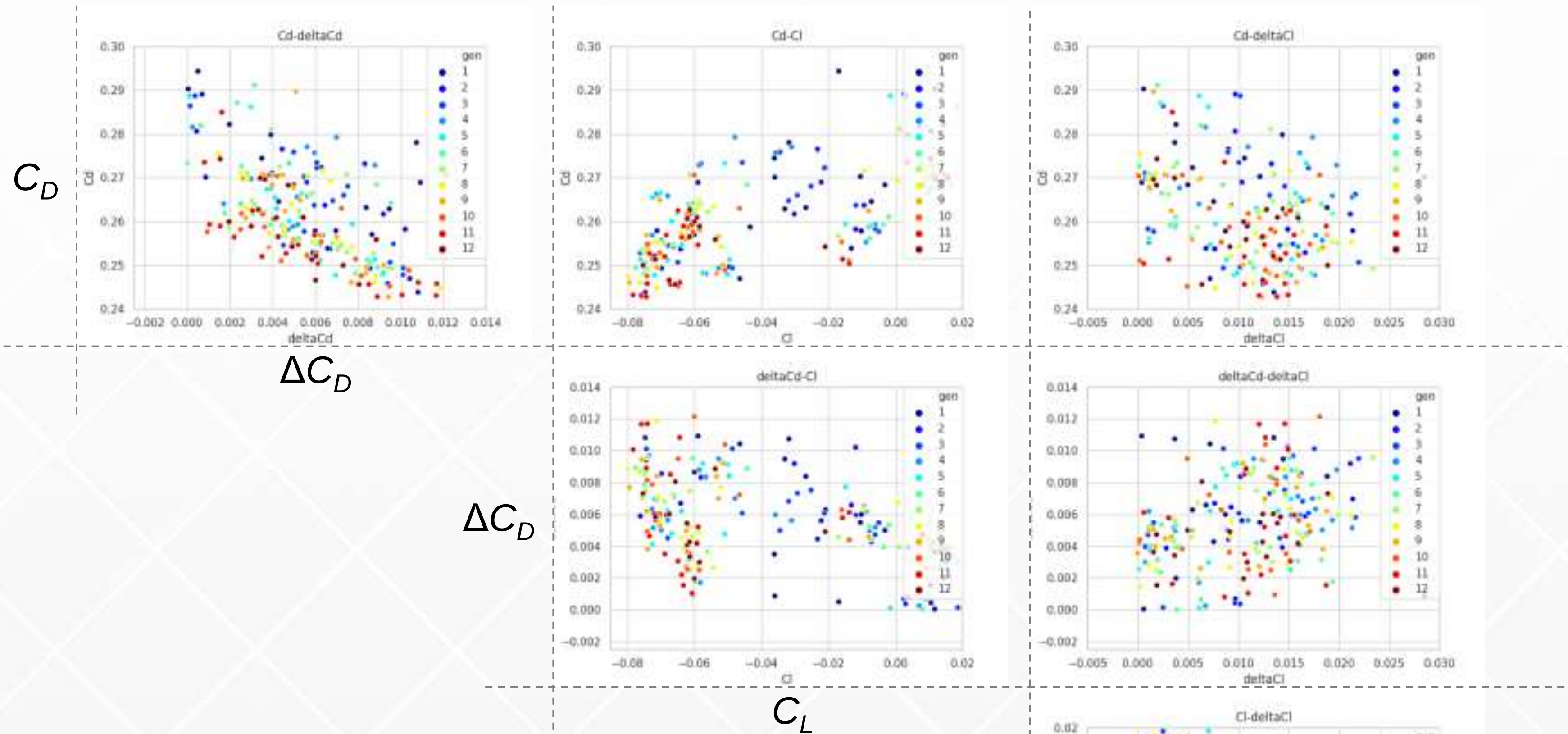
Aerodynamic characteristics
(Objective function)
Text

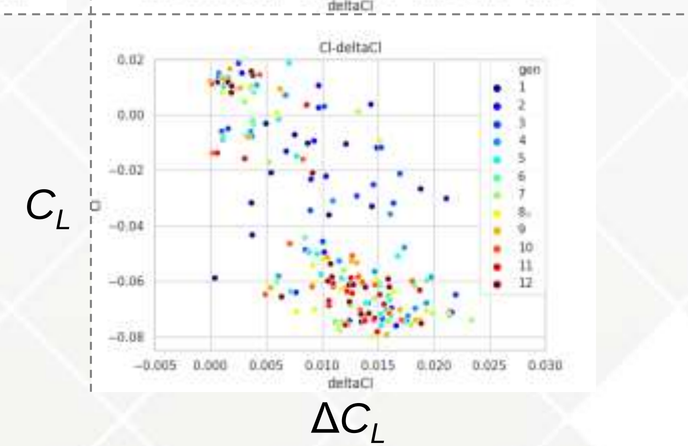


Shape parameters
(Design variables)
Text



Results of multi-objective shape optimization



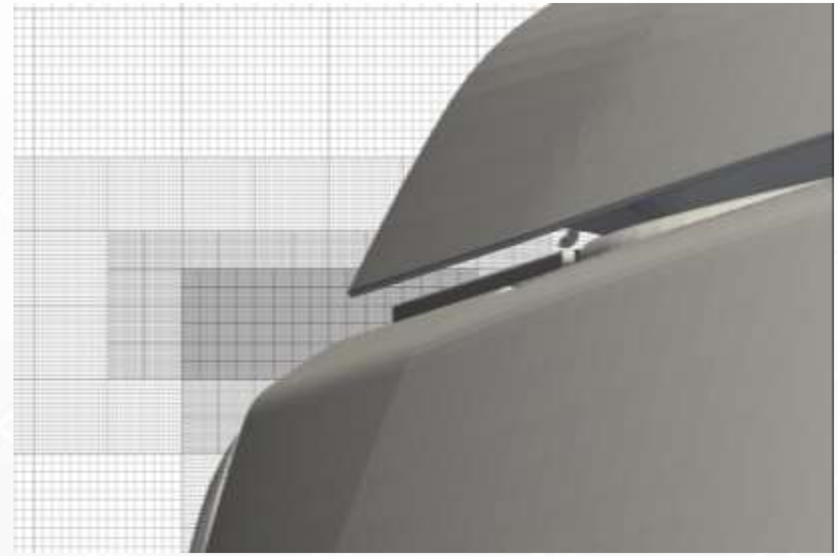


- Genetic Optimization until 12th generations.
- Tradeoff between some objective functions such as Cd and ΔCd.

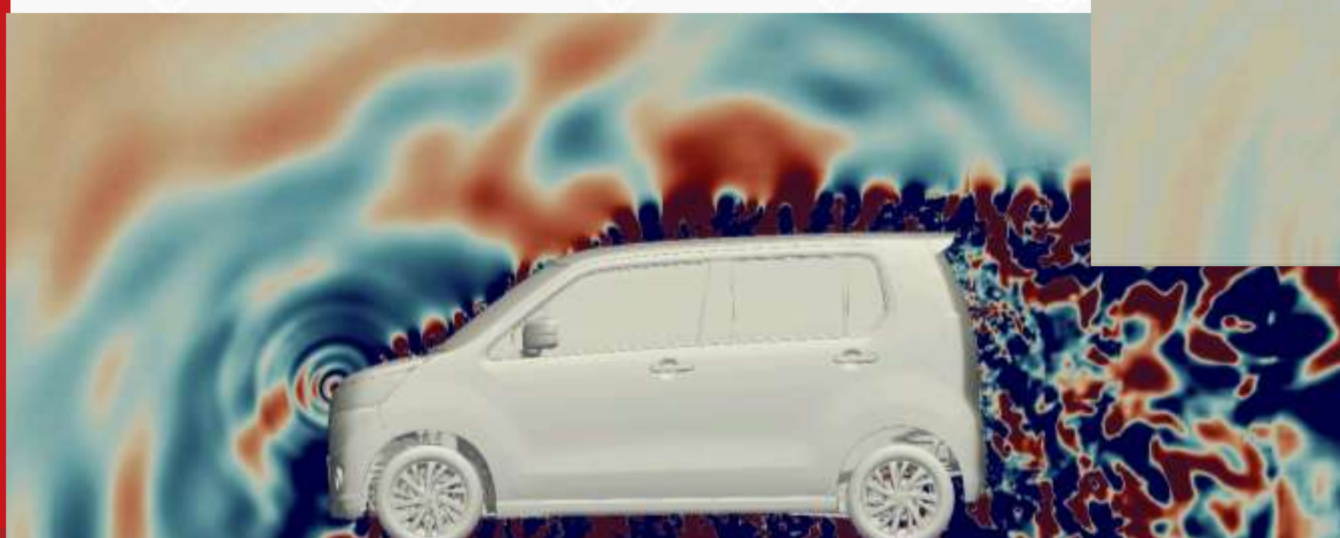
Real-World Simulation

Narrow band noise from a full-scale vehicle

- **Acoustic feedback noise generated at a small gap.**
- **Very peaky and uncomfortable…**
- **For the prediction, full coupling simulation of flow and acoustics is needed.**



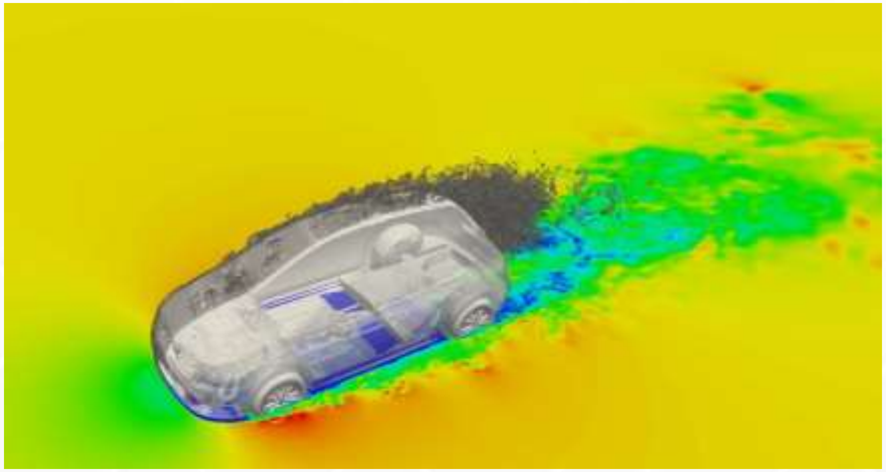
Grid size	0.2 mm/1.6mm
Cube num.	471,059
Cell num.	1,929,457,664
Core num.	13086x8 / 50 hrs



Real-World Simulation

Coupled Aerodynamics, Vehicle Motion and Driver's Reaction Simulation

- HPC-CFD for flow around a vehicle (Aerodynamics)
- Multi-Body vehicle motion analysis (6DoF body motion with suspension and steering)
- Autonomous Vehicle Motion by a Driver's steering wheel, accelerator/braking actions
- Lane changing motion at 100km/h

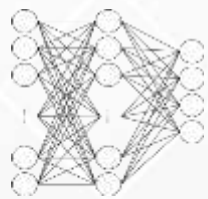


Toward FUGAKU

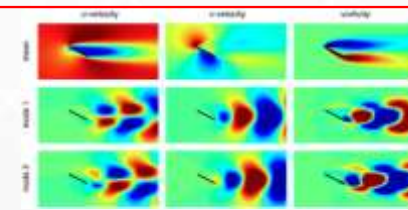
Coupling Data Science and HPC-CFD for Innovative CAE

- **Innovative Industrial CAE Solution by a Fusion of Data Science and High-Performance Computing Simulation**
- **Machine/Deep Learning, Data Assimilation, Multi-Objective Optimization…**
  - Surrogate Model: Realizing real time evaluation of aerodynamic performance such as drag and lift force.
  - Reduction Model: Realizing complicated real world simulation and reproducing flow field at lower cost.

Surrogate Model

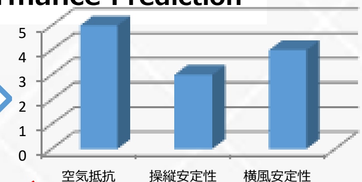


Neural Network



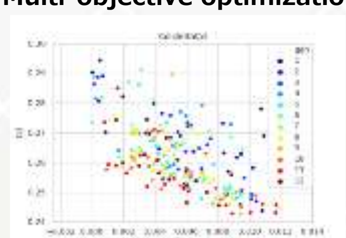
Reduction Model by Proper-Orthogonal Decomposition

Real Time Performance Prediction



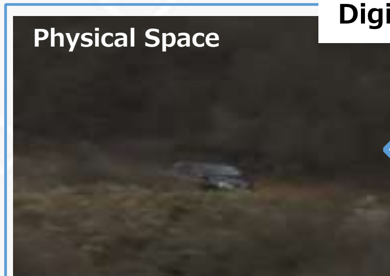
Co-operation design

Multi-objective optimization



Digital Twin

Physical Space



Cyber Space

Virtual on-road test

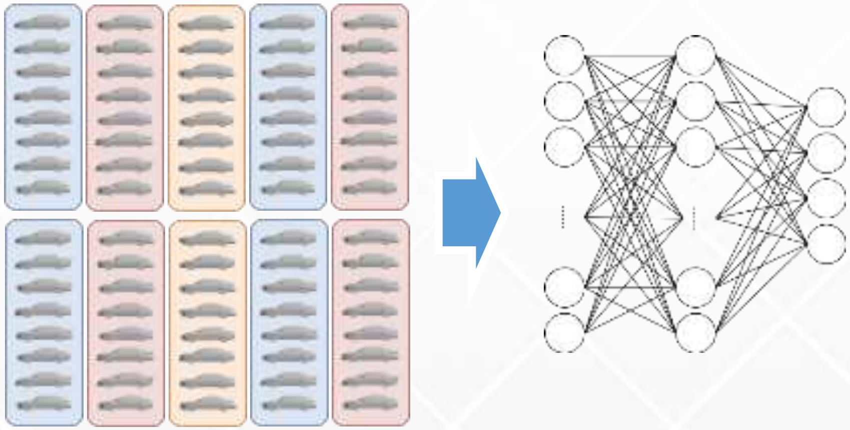
Training AI for automatic driving

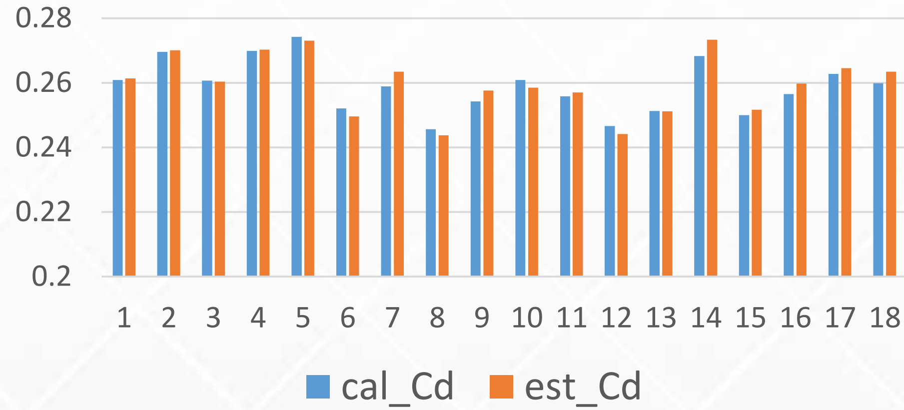
RIKEN AICS

Toward FUGAKU

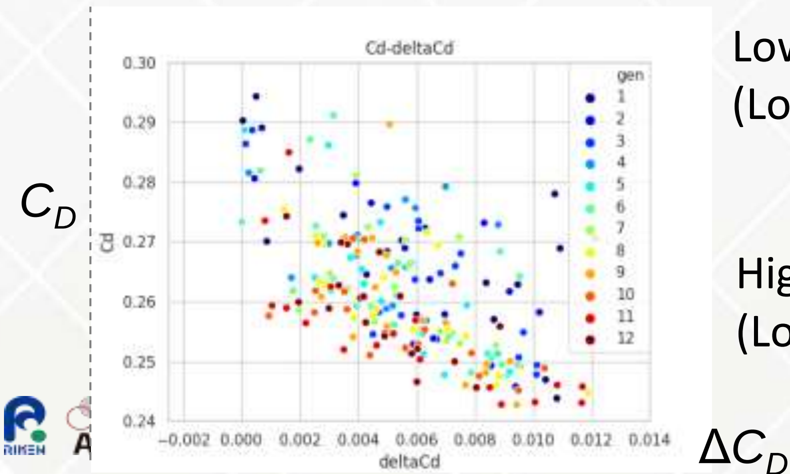
Shape Optimization based on a Surrogate Model

- **Development of a Surrogate Model based on Neural Network.**
  - Hundreds of HPC-CFD results as teaching data.
  - Prediction of Drag less than 5% error against the HPC simulation results.





- **Coupling the Surrogate Model with Multi-Objective Genetic Algorithm.**
  - AI proposes high-performance vehicle shape.



Low emission car
(Lowest CD)

High crosswind stability car
(Lowest ΔCd)

Toward FUGAKU

Reduction Model of the Navier-Stokes Simulation

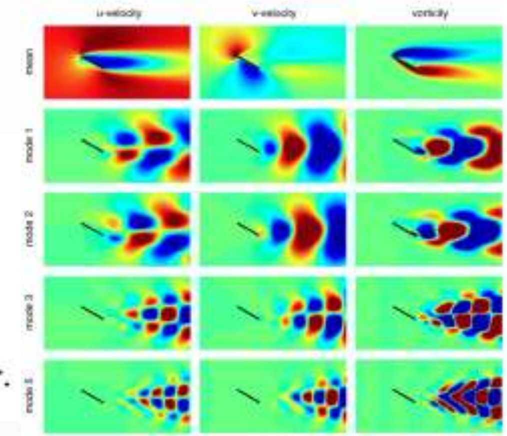
- **Reduced order model by Proper-Orthogonal Decomposition.**
  - Full flow simulation results are projected on the reduced base functions.

$$\boldsymbol{u}(\boldsymbol{x},t) = \sum_{j=0}^{r} a_j(t)\boldsymbol{\varphi}_j(\boldsymbol{x})$$

$$\frac{da_i}{dt} = \sum_{j=0}^{r}\sum_{k=0}^{r} F_{ijk}a_j a_k + \sum_{j=0}^{r} G_{ij}a_j,$$

$$F_{ijk} = -\left\langle \boldsymbol{\varphi}_i, \boldsymbol{\varphi}_j \cdot \nabla \boldsymbol{\varphi}_k \right\rangle,$$

$$G_{ij} = \frac{1}{Re}\left\langle \boldsymbol{\varphi}_i, \nabla^2 \boldsymbol{\varphi}_j \right\rangle, \quad i = 1, \ldots, r.$$



$a_0(t)\boldsymbol{\varphi}_0(\boldsymbol{x})$

$a_1(t)\boldsymbol{\varphi}_1(\boldsymbol{x})$

$a_2(t)\boldsymbol{\varphi}_2(\boldsymbol{x})$

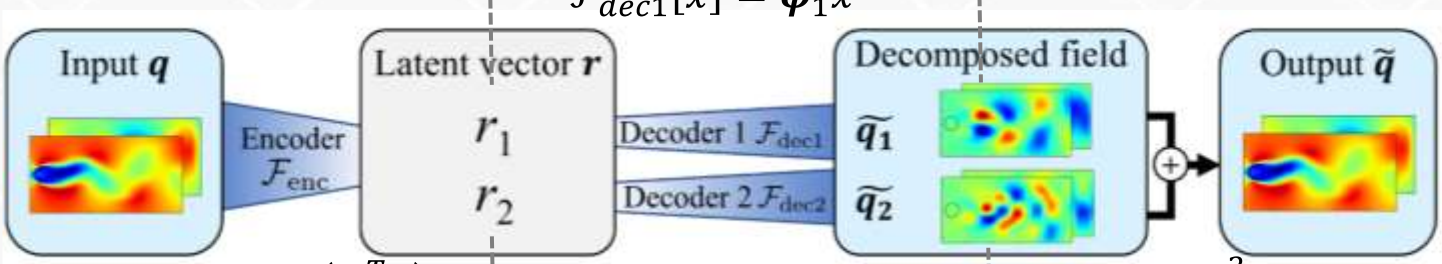
$a_3(t)\boldsymbol{\varphi}_3(\boldsymbol{x})$

$a_5(t)\boldsymbol{\varphi}_5(\boldsymbol{x})$

- **The base functions are obtained by Neural Network(Murata).**

Inner product | **Scaling** | **Summation**

$\mathcal{F}_{dec1}[x] = \boldsymbol{\varphi}_1 x$

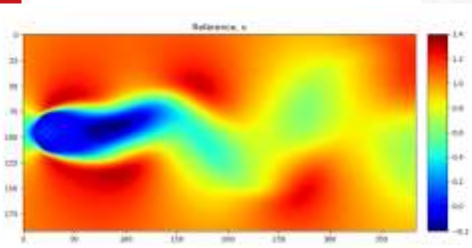


$$\mathcal{F}_{enc}[\boldsymbol{x}] = \begin{pmatrix} \boldsymbol{\varphi}_1^T \boldsymbol{x} \\ \boldsymbol{\varphi}_2^T \boldsymbol{x} \end{pmatrix}$$

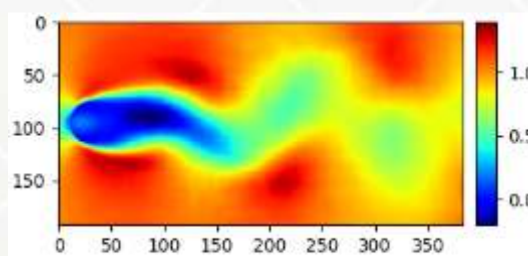
$$\mathcal{F}_{dec2}[x] = \boldsymbol{\varphi}_2 x$$

$$\boldsymbol{P}\boldsymbol{x} = \sum_{k=1}^{2} \boldsymbol{\varphi}_k \boldsymbol{\varphi}_k^T \boldsymbol{x}$$

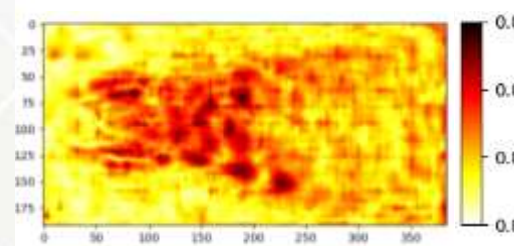
Full-NS simulation



10,000 samples
2,000 epochs



L^2 Norm (Time averaged)



Concluding Remarks

Computer simulations create the future

- *CFD use in industries are conservative, which is just an alternative to conventional experiments, so far···*
- *HPC expands the possibility of CFD by exceeding their accuracy and applying to real-world problems, while data structure is the key to massively utilize HPC environment.*
- *Hierarchically structured data realized very fast and real-world aerodynamics simulation on the K computer.*
- *Coupling data science and HPC simulation will create next-generation Computer-Aided Engineering on FUGAKU.*
  - *Surrogate model for real time evaluation.*
  - *Reduction model for real world simulation.*

Thanks to Industrial Partners

Consortium for next-generation Automotive CAE using HPC (Nov., 2017~)

BRIDGESTONE
SUBARU
HONDA
NISSAN
mazda
HINO
MITSUBISHI MOTORS
DENSO
SUZUKI
TOYO TIRES driven to perform
TOYOTA
CalsonicKansei
AISIN
KOITO
北海道大学 HOKKAIDO UNIVERSITY
東京大学 THE UNIVERSITY OF TOKYO
KOBE UNIVERSITY
RIKEN
豊橋技術科学大学 TOYOHASHI
SEIKEI
JAXA
HIROSHIMA UNIVERSITY

Consortium for Combustion System CAE (April, 2018~)

北海道大学 HOKKAIDO UNIVERSITY
京都大学 KYOTO UNIVERSITY
大阪大学 OSAKA UNIVERSITY
JAXA
RIKEN
CRIEPI
九州大学 KYUSHU UNIVERSITY
三菱日立パワーシステムズ MITSUBISHI HITACHI POWER SYSTEMS
Kawasaki Powering your potential
TOSHIBA
IHI Realize your dreams
エネルギー・フロンティア TOKYO GAS

Consortium for Construction CFD for Wind-Resistance

東京工業大学 Tokyo Institute of Technology
KOBE UNIVERSITY
RIKEN
建築研究所 Building Research Institute
大林組 OBAYASHI
鹿島 KAJIMA CORPORATION
清水建設 SHIMIZU CORPORATION
大成建設 TAISEI
竹中工務店
前田建設 MAEDA
nikken.jp 日建設計