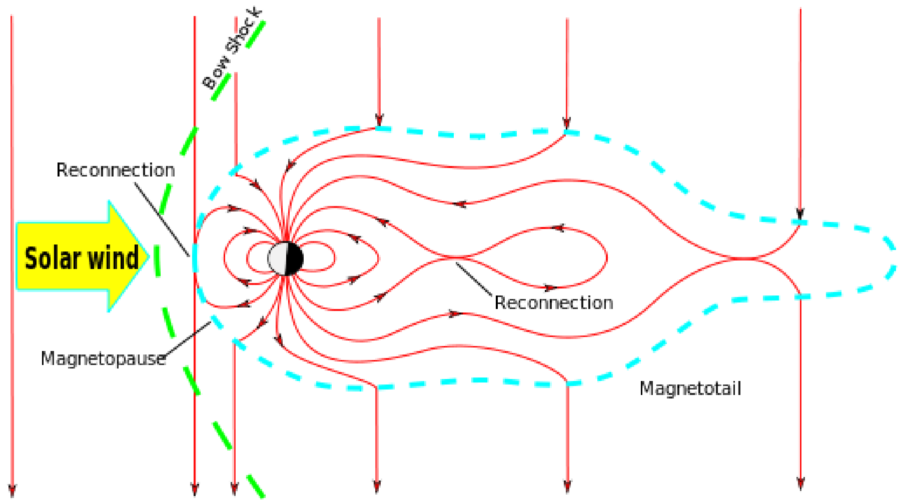
2018/02/26
2017年度第2回 計算科学フォーラム

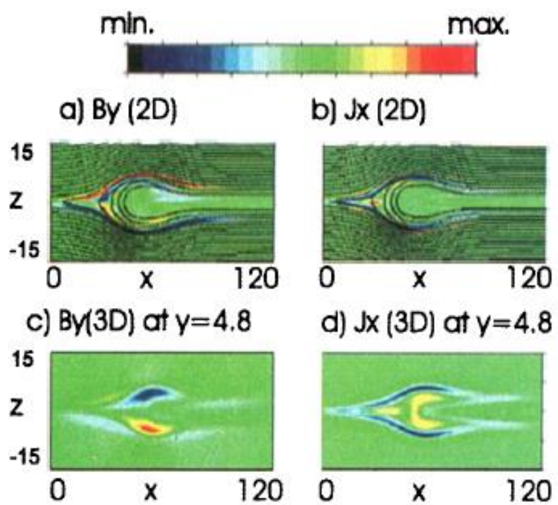
乱流の準直接計算技術の工学応用

みずほ情報総研株式会社
山出吉伸

何故、計算するのか？



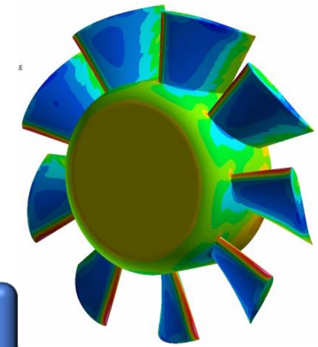
出典：https://en.wikipedia.org/wiki/Geomagnetic_storm

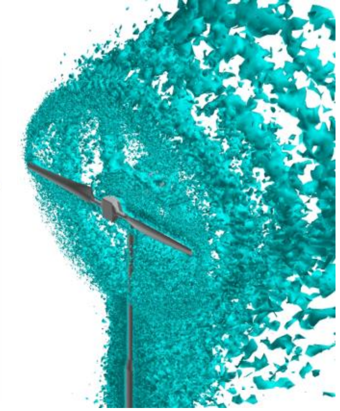


~1999 年
宇宙：L: 10^7 [m]

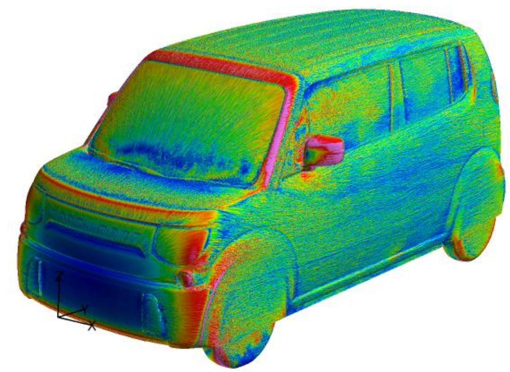
1999~2002 年
地球：L: 10^4 [m]

ターボ機械

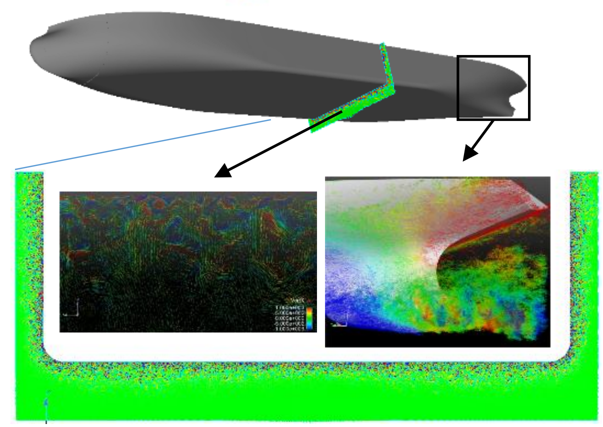




車



船舶



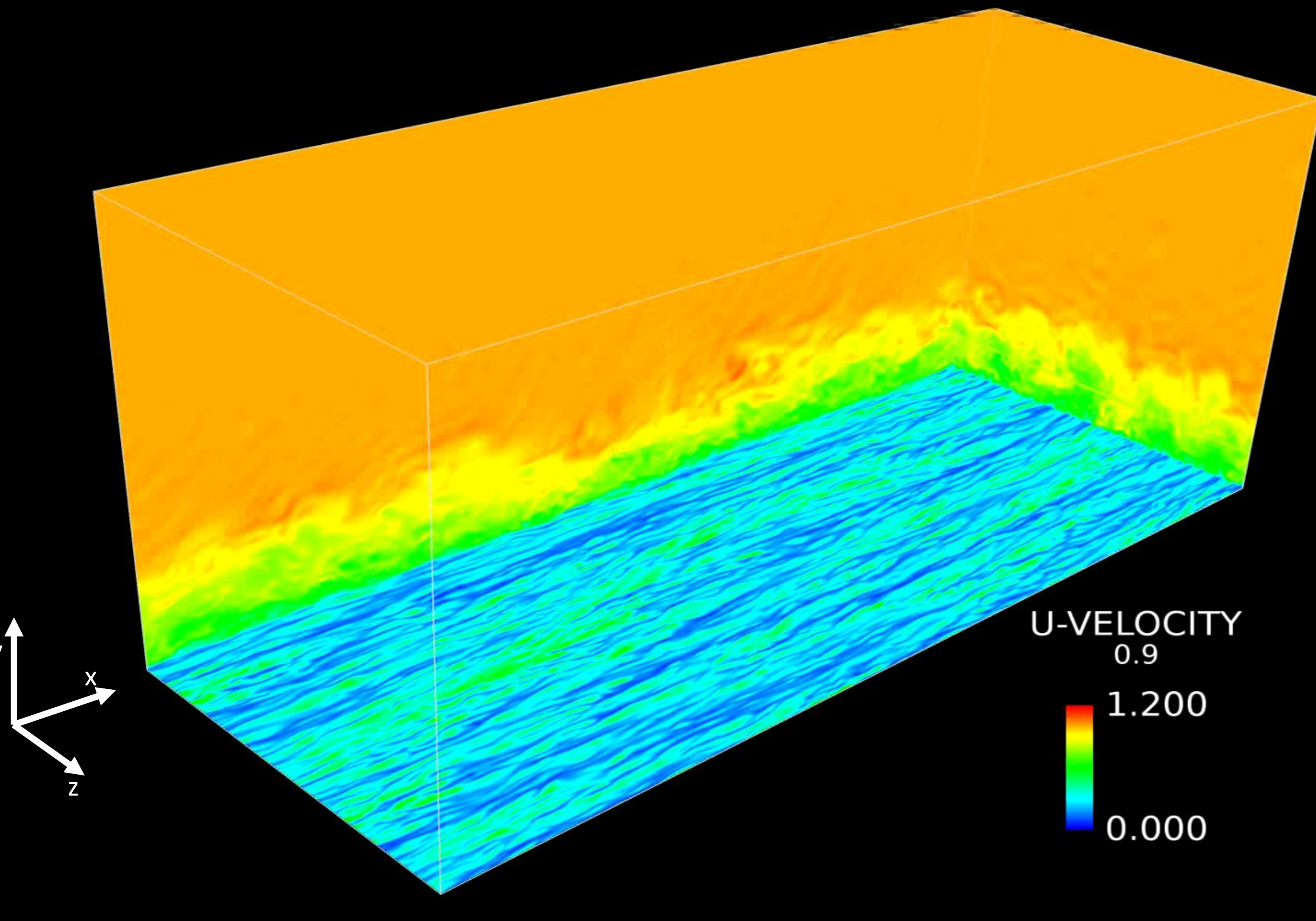
2002年～
機械：L: 10^{-1} ～10^3 [m]

講演の内容

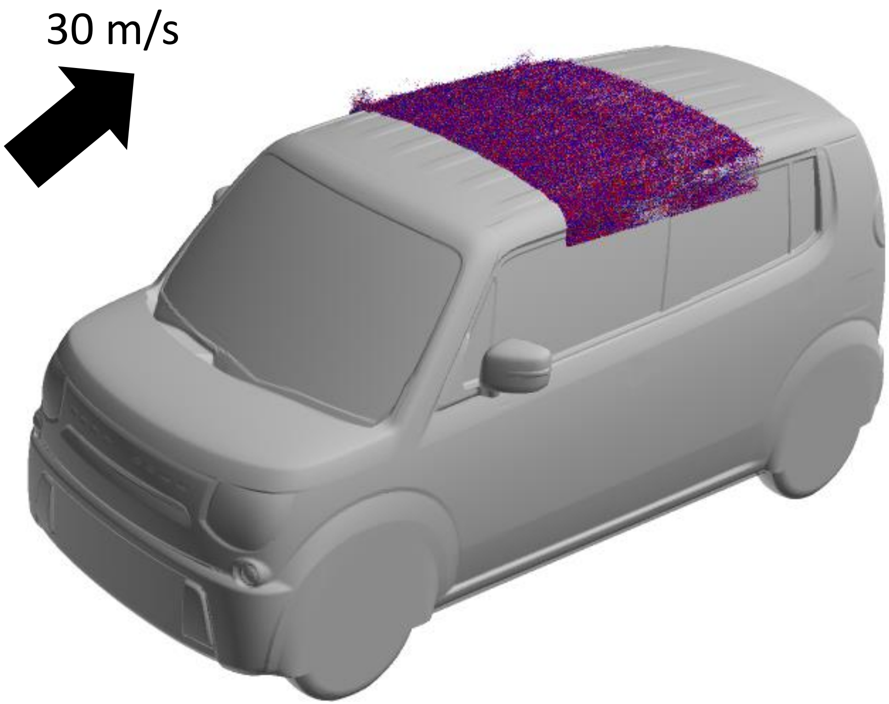
- ■はじめに
- ■準直接計算の工学応用事例
  - ✓船体抵抗予測技術の開発
  - ✓車室内騒音の予測
  - ✓ポンプ吸い込水槽の吸込渦発生メカニズム
  - ✓遠心送風機から発生する空力騒音の予測
  - ✓風車
- ■ポスト京にむけて

1. はじめに

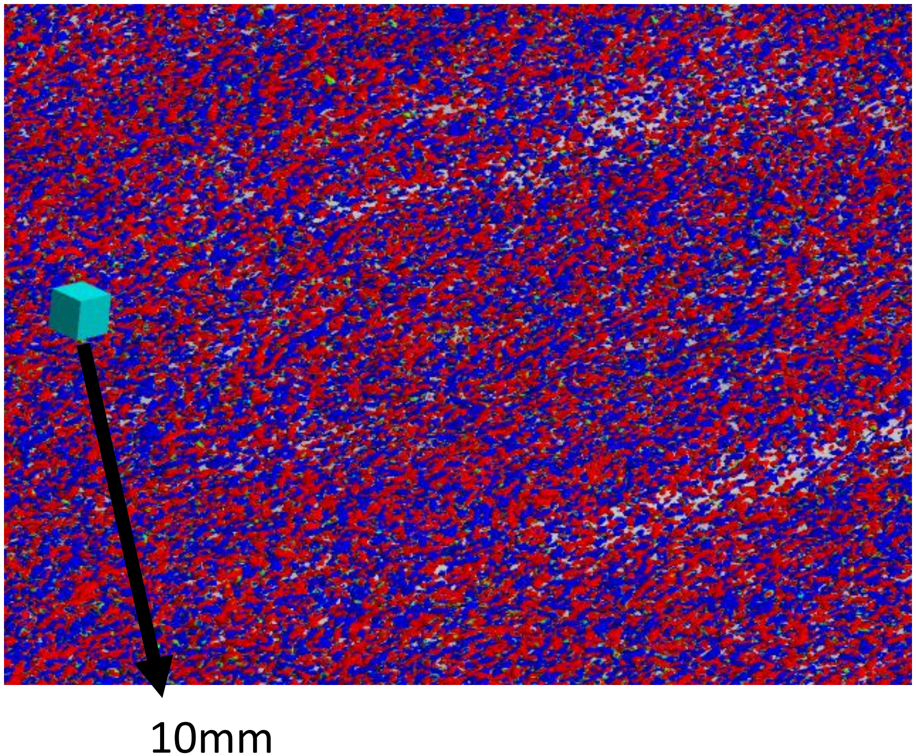
乱流の準直接計算



車体まわり流れの準直接計算



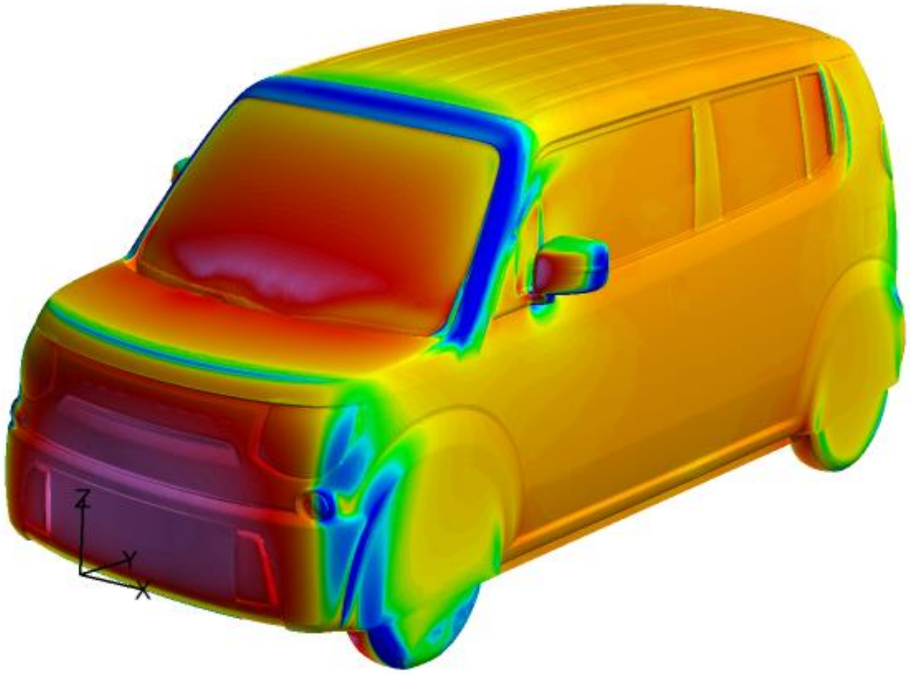
車体まわり流れの準直接計算
(400億グリッド）

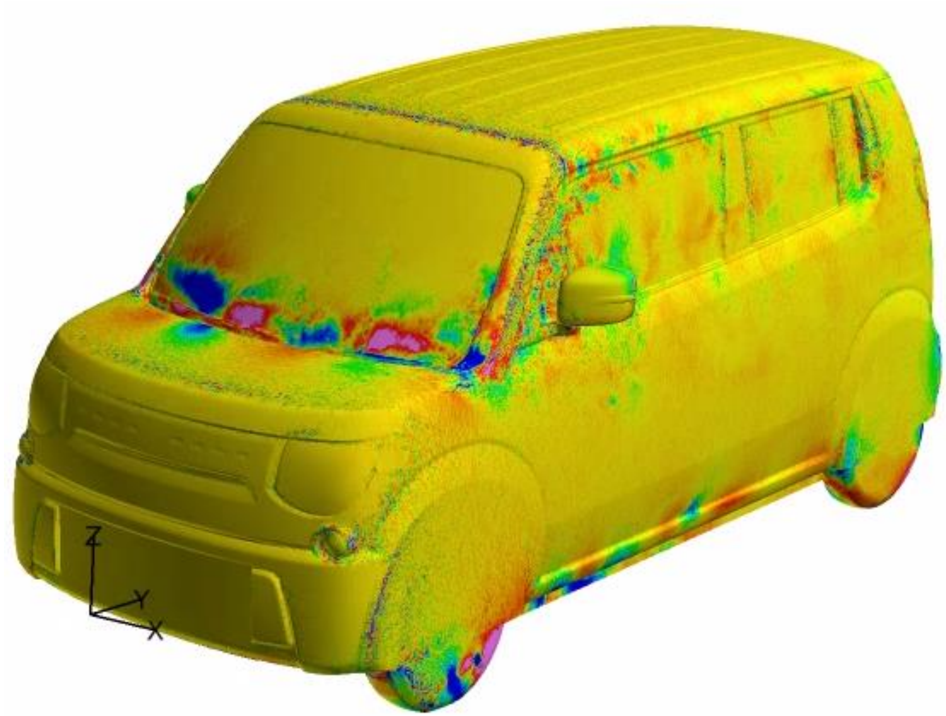


車両上面に発達する乱流境界層における渦の可視化結果

車体表面における0.5mm程度の渦の運動を計算

車体まわり流れの準直接計算





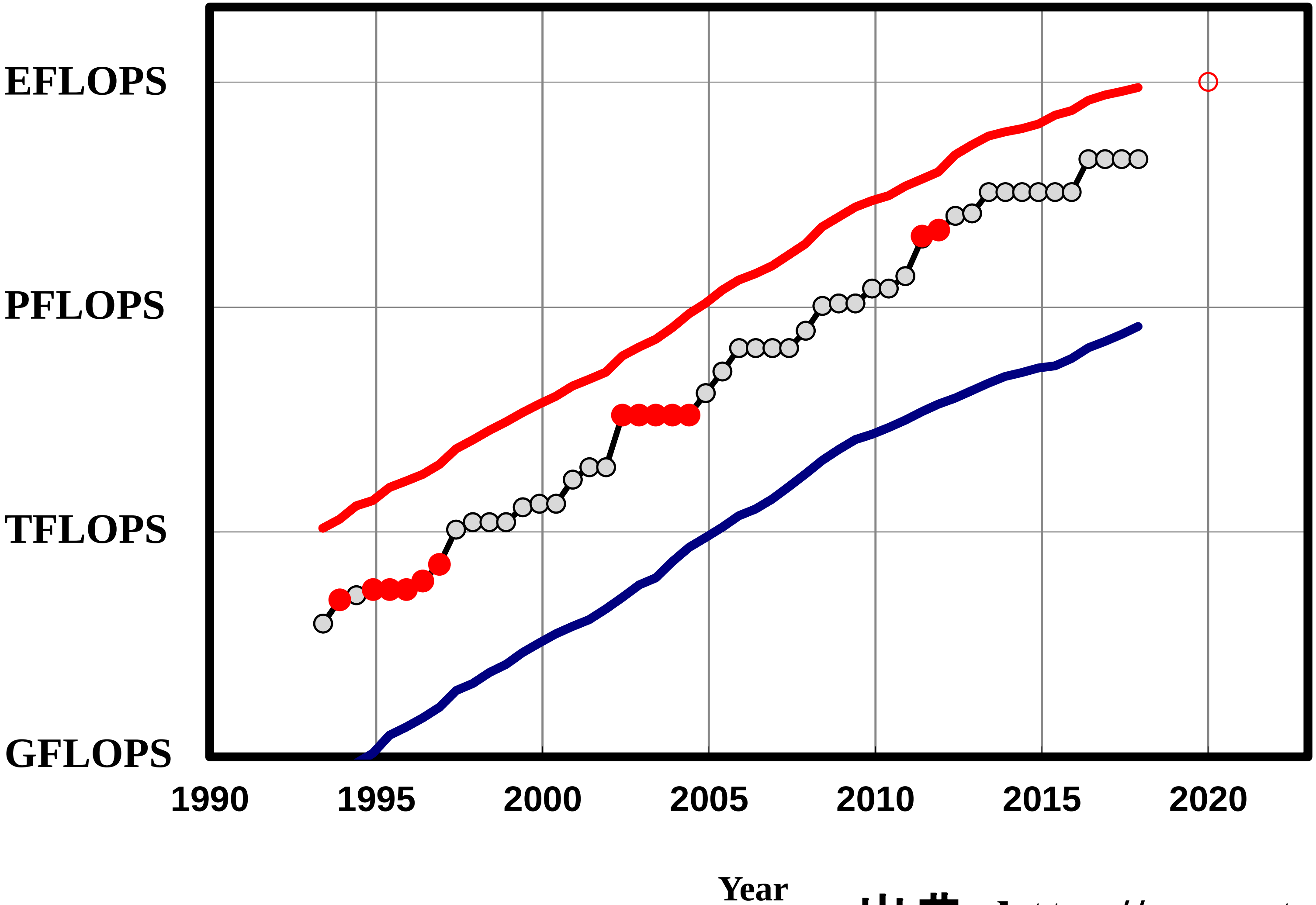
定常圧力場

→C_d（燃費）

変動圧力場

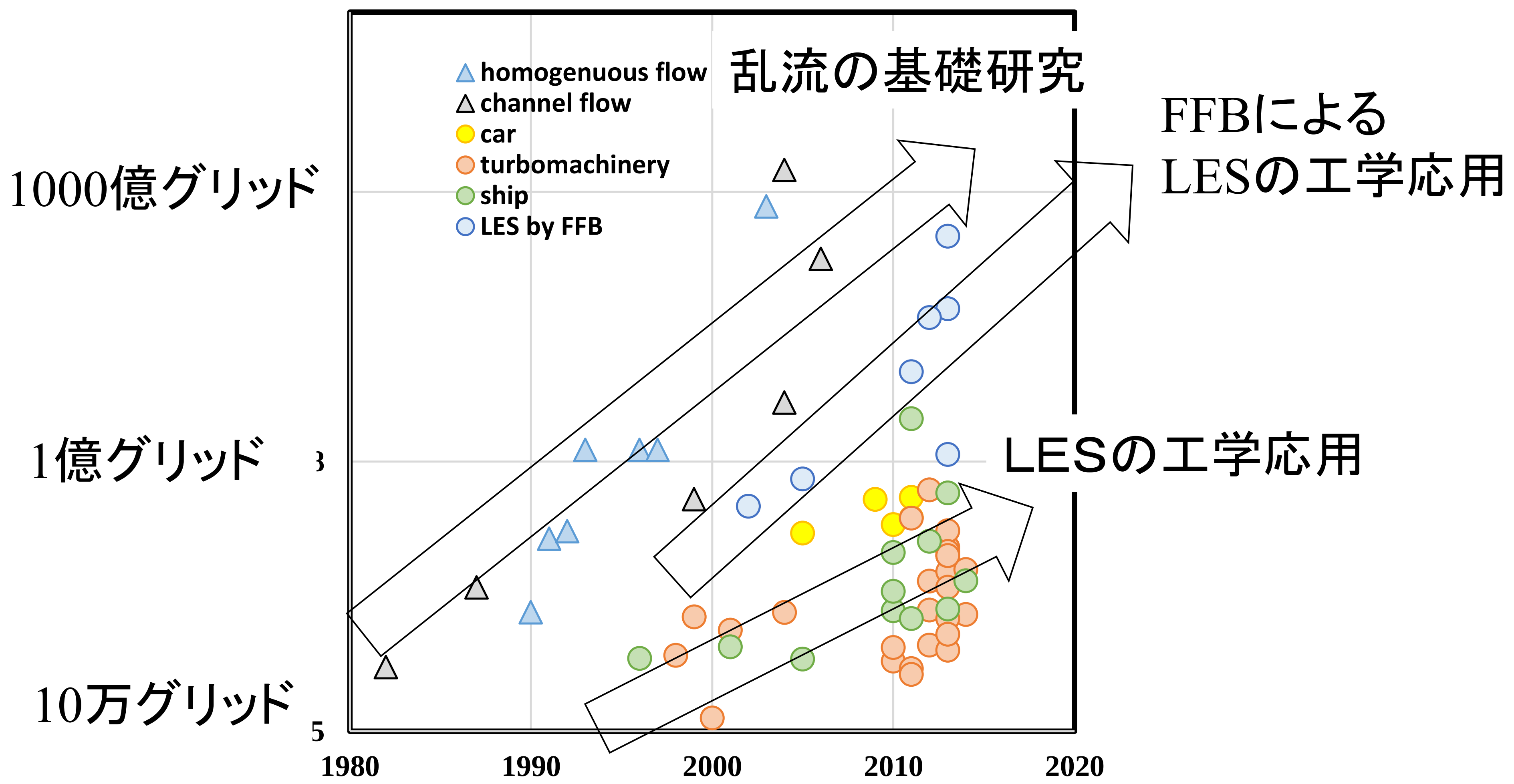
→非定常空気力（走行安定性）
→車室内騒音（乗り心地）

計算機の動向：top500



出典：http://www.top500.org/

準直接計算技術の工学応用



2.2 準直接計算の工学応用2
車室内騒音の予測

Introduction

Background & Objective

Engine Noise

Aeroacoustics Noise

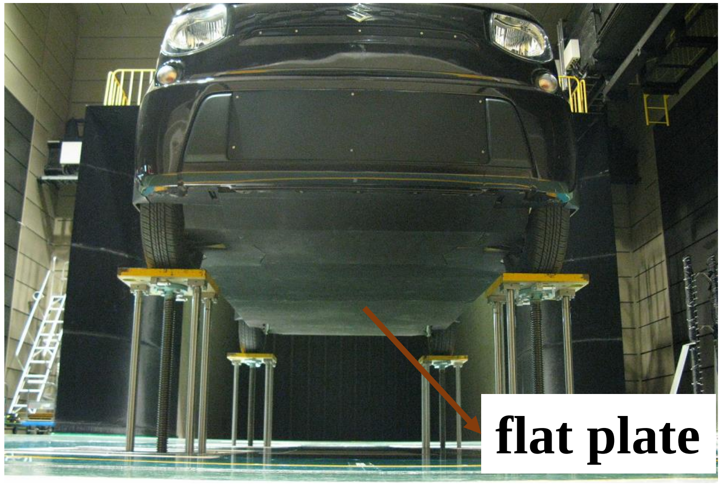
Road Noise

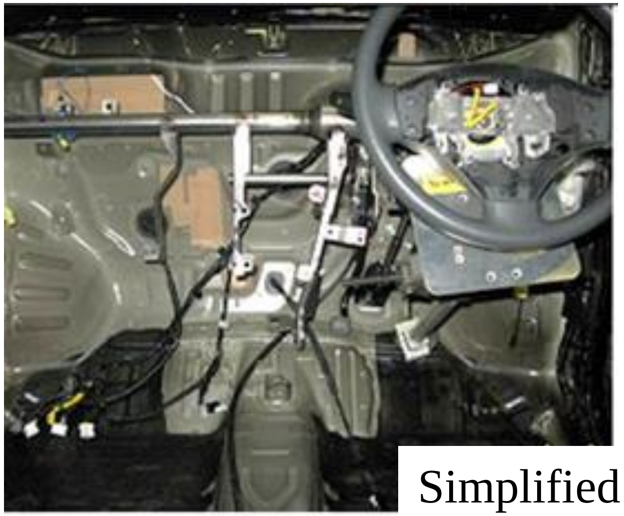
Reduction of Interior Noise

↑

Prediction and Understanding of Interior Noise

Test Car



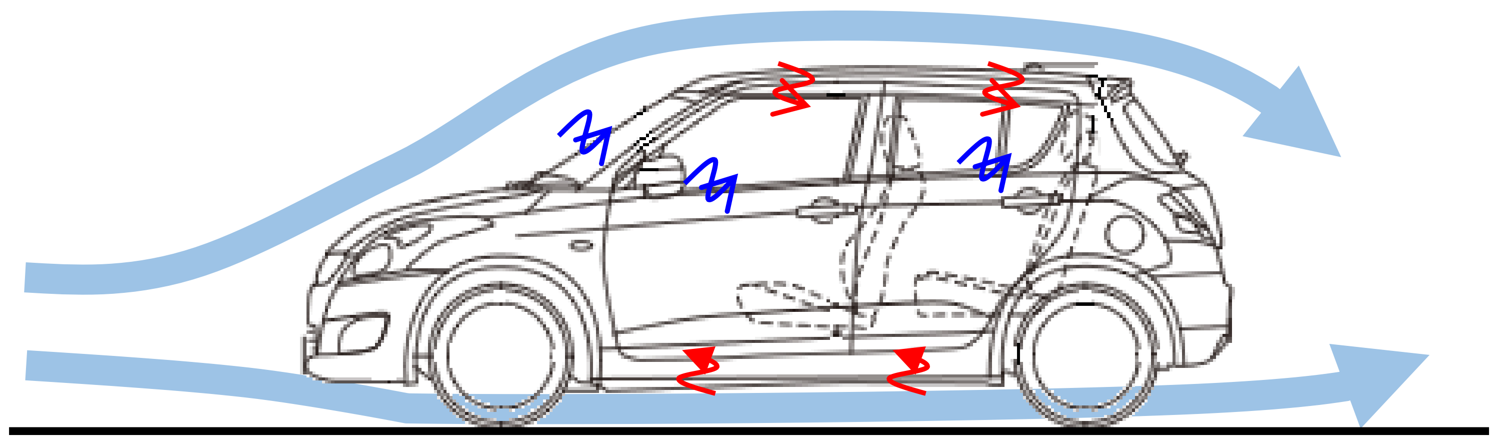


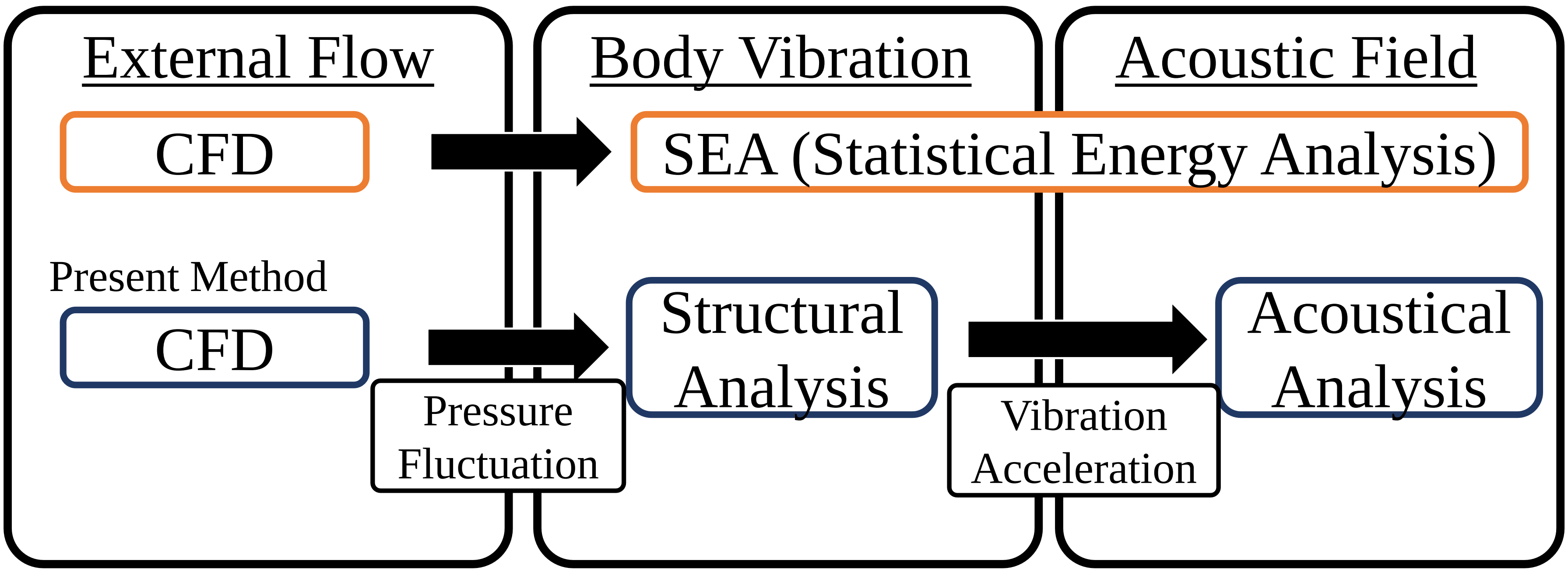
Covers and flat plate
to simplify external flow

All interior components have been
removed to simplify internal acoustics

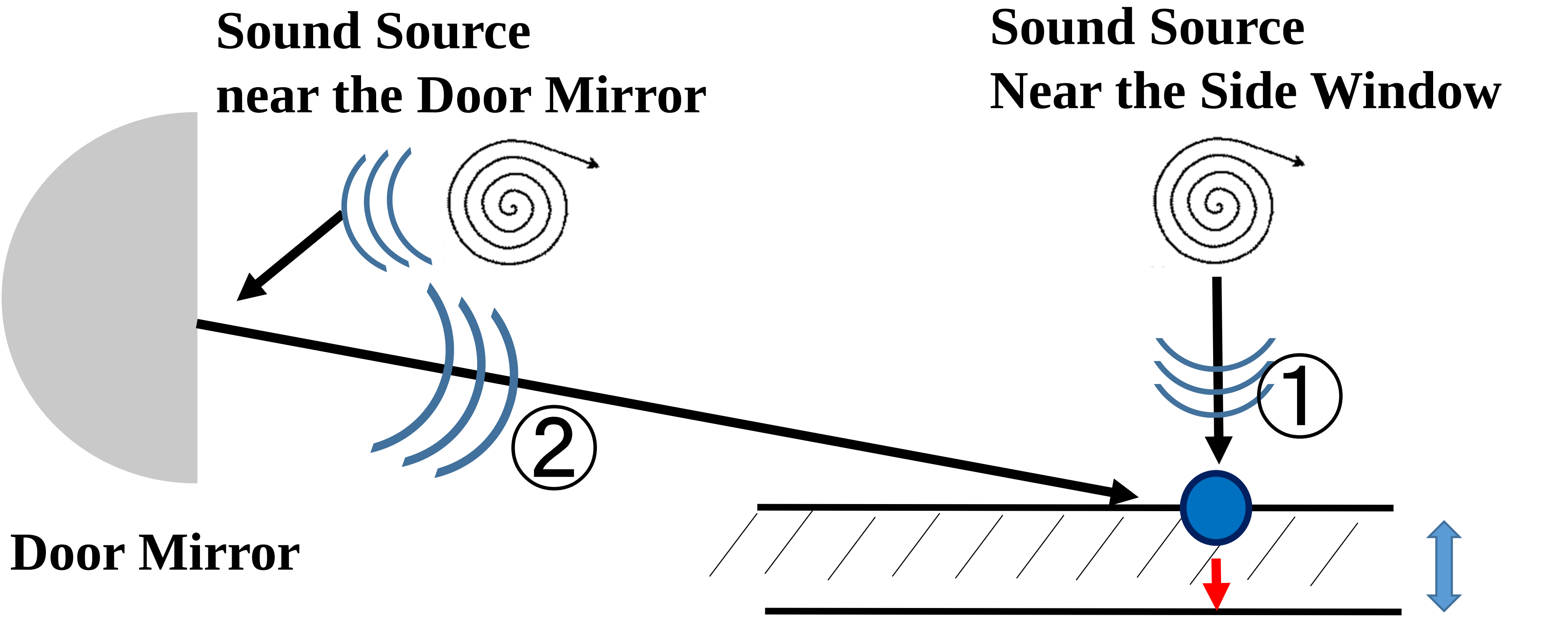
Methodology

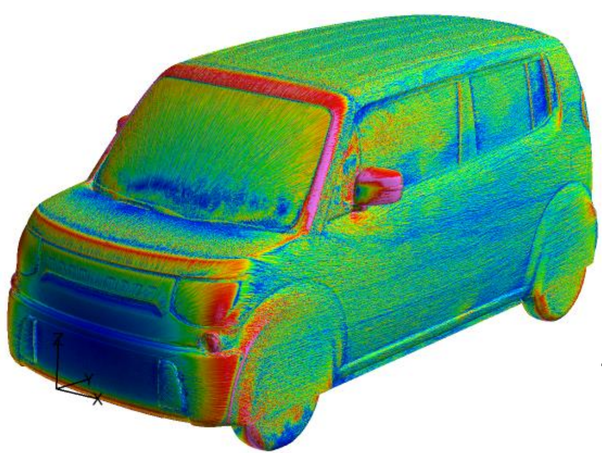
Direct Simulation of Interior Noise



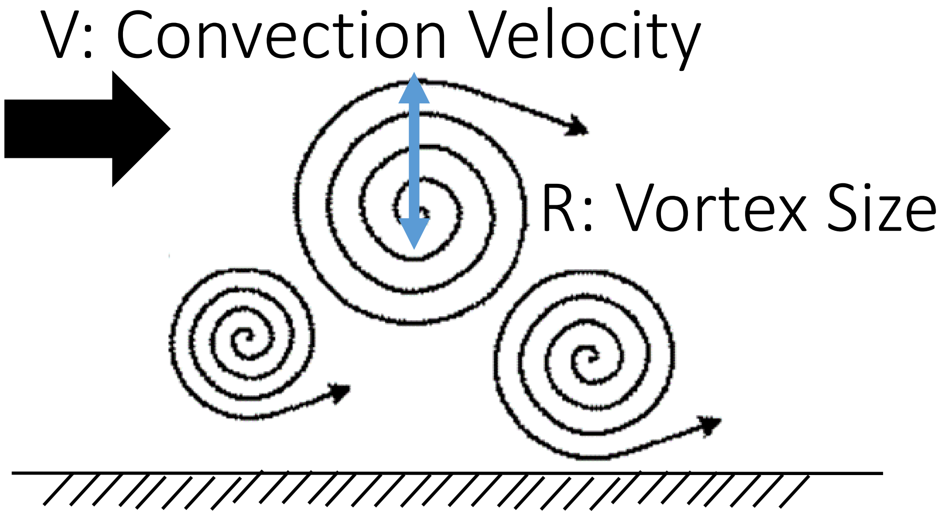


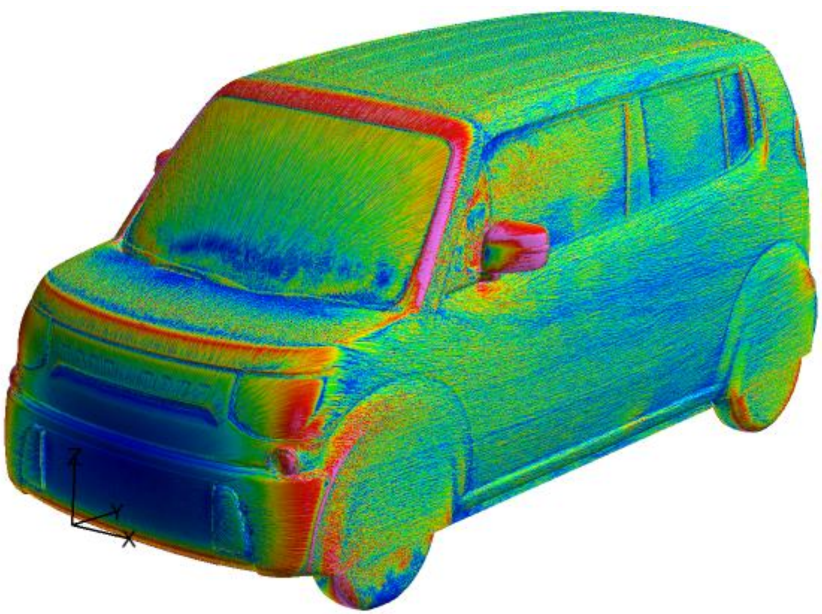
Incompressible Flow Solver





Wall Resolving LES of Exterior Flow





- Frequency

$$F = \frac{V}{2\pi R}$$

- In this case,

F=2.0kHz

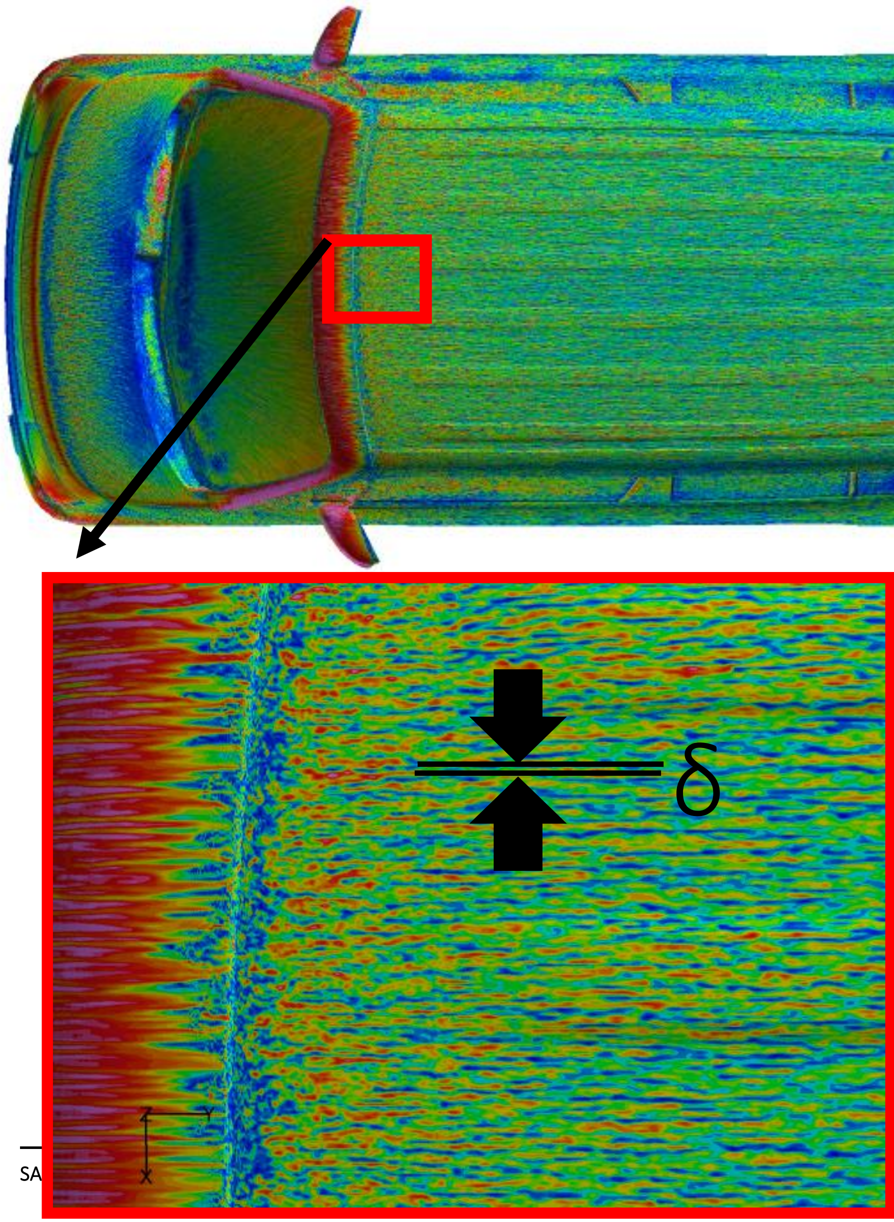
V=30 m/s

$\Rightarrow$ R=2.4 mm

- Grid resolution

1.6 mm

Wall Resolving LES of Exterior Flow



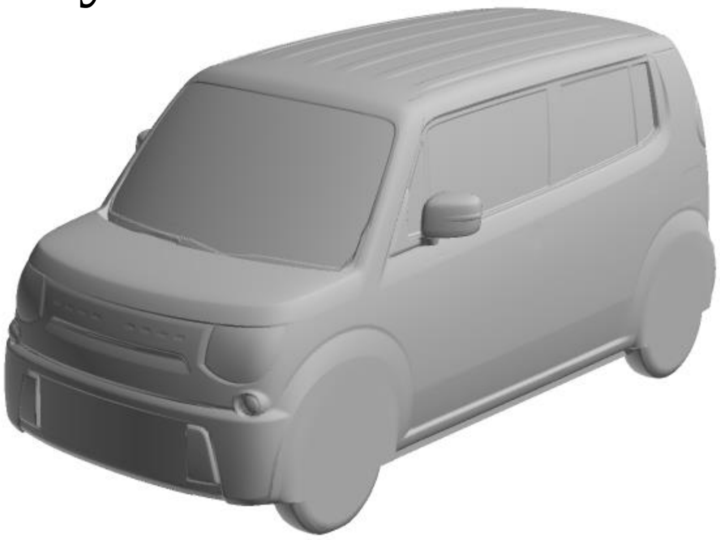
- Diameter of Vortices 0.3 mm

($\delta^+ = \delta U_\tau / \nu \sim 30$)

Numerical Conditions

Computational Model

- Car Shape: Simplified Commercial Car Model (SUZUKI)
- Computational Domain: 40m × 18m × 9.5 m
- Boundary Condition:
  - ✓ Inlet: Constant Inlet Velocity (30m/s)
  - ✓ Outlet : Constant Pressure
  - ✓ Other: Non-Slip
- SGS model: Dynamic Smagorinsky Model



Computational Cases

	Base mesh	5 billion mesh	40 billion mesh
Number of Grids	80 million	5 billion	40 billion
Wall Normal Grid Resolution [mm]	0.8	0.2	0.1
Number of CPUs	1,204	3,456	39,998
Cal. Time [sec]	1.62	0.28	0.01
Flow Visualization	○	○	○
Comparisons with Measurements	○	○	x

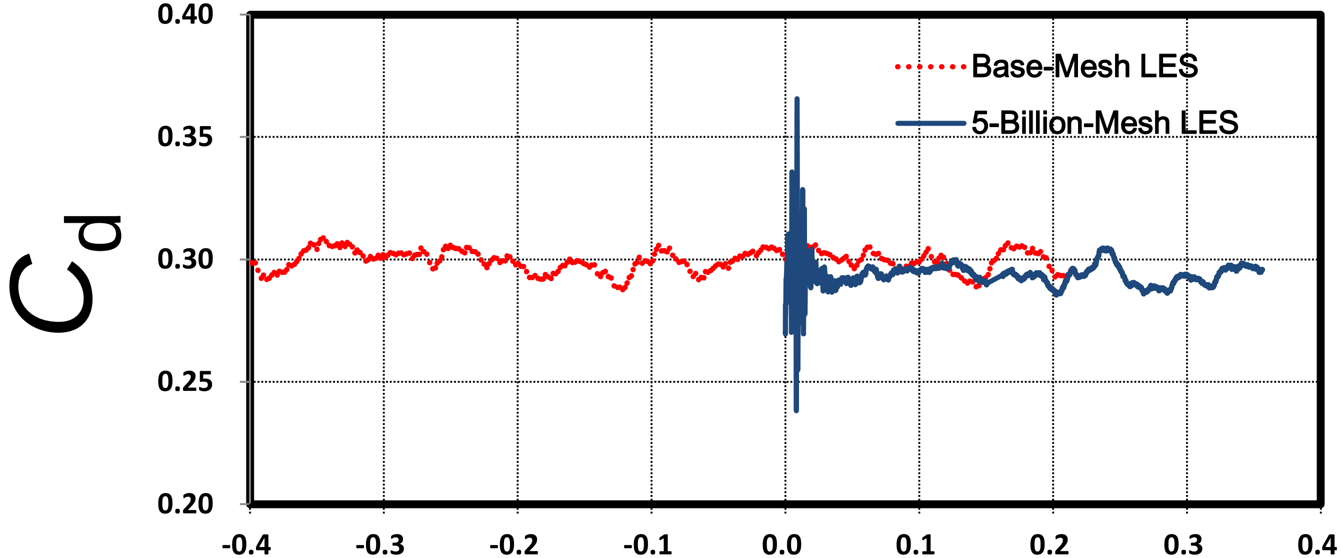
Super Computer, K

Results

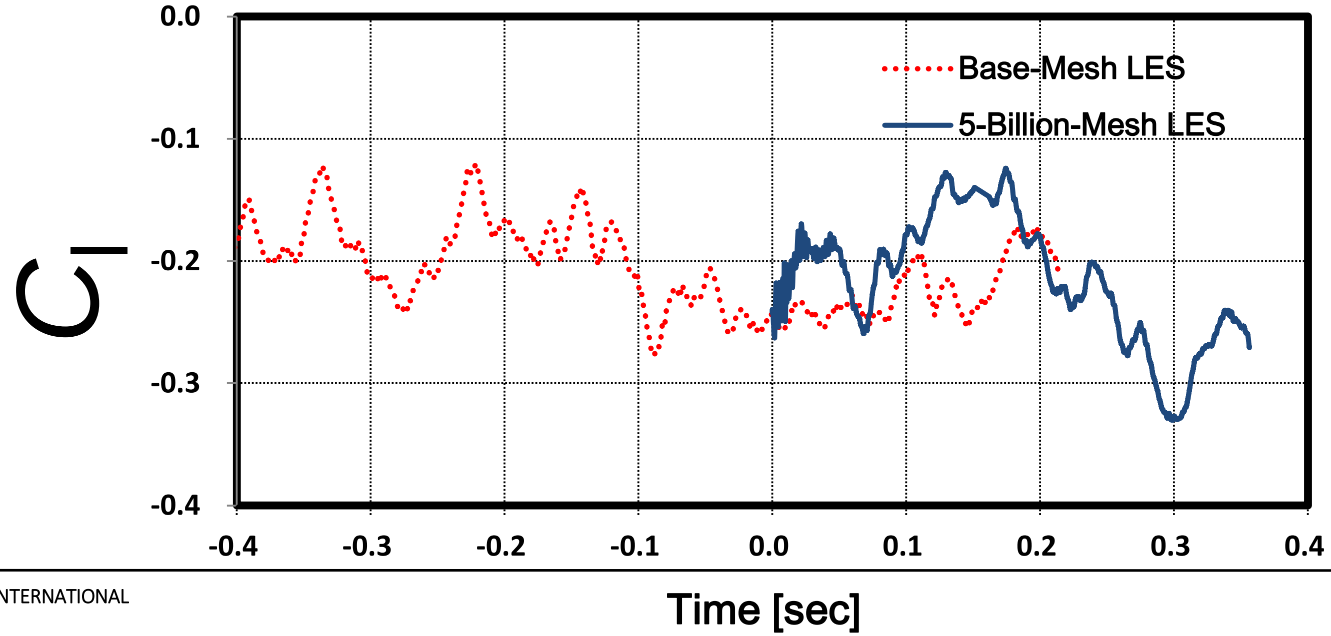
Computational Results

- C_d and C_l
- Visualization
  - ✓ Pressure (time average and RMS)
  - ✓ Vortical Structure
  - ✓ Pressure Fluctuations
- Power Spectra of Pressure Fluctuations
- Acoustic and Hydrodynamic Pressure Fluctuations

C_d & C_l



Measured: 0.300

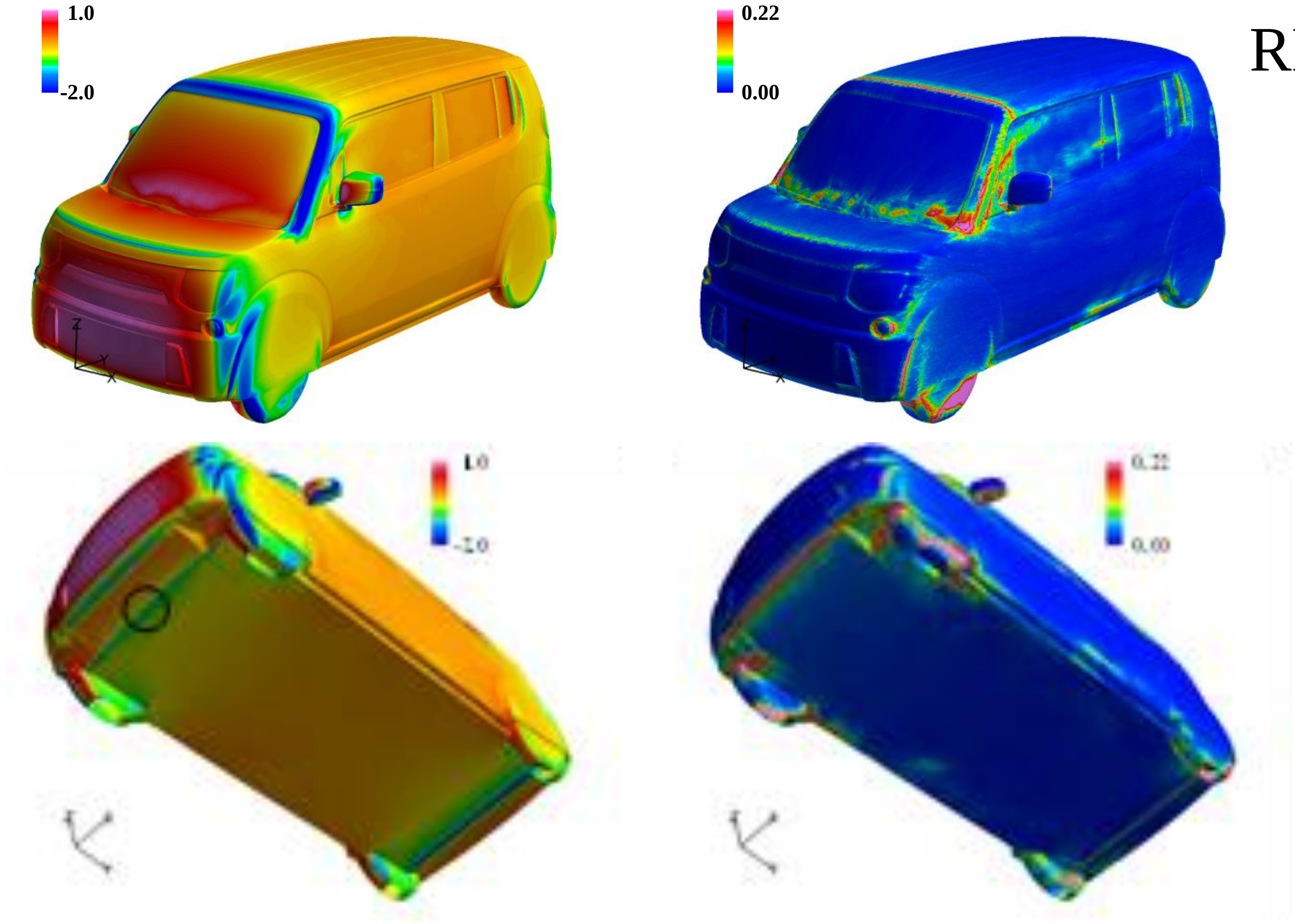


Measured: -0.019

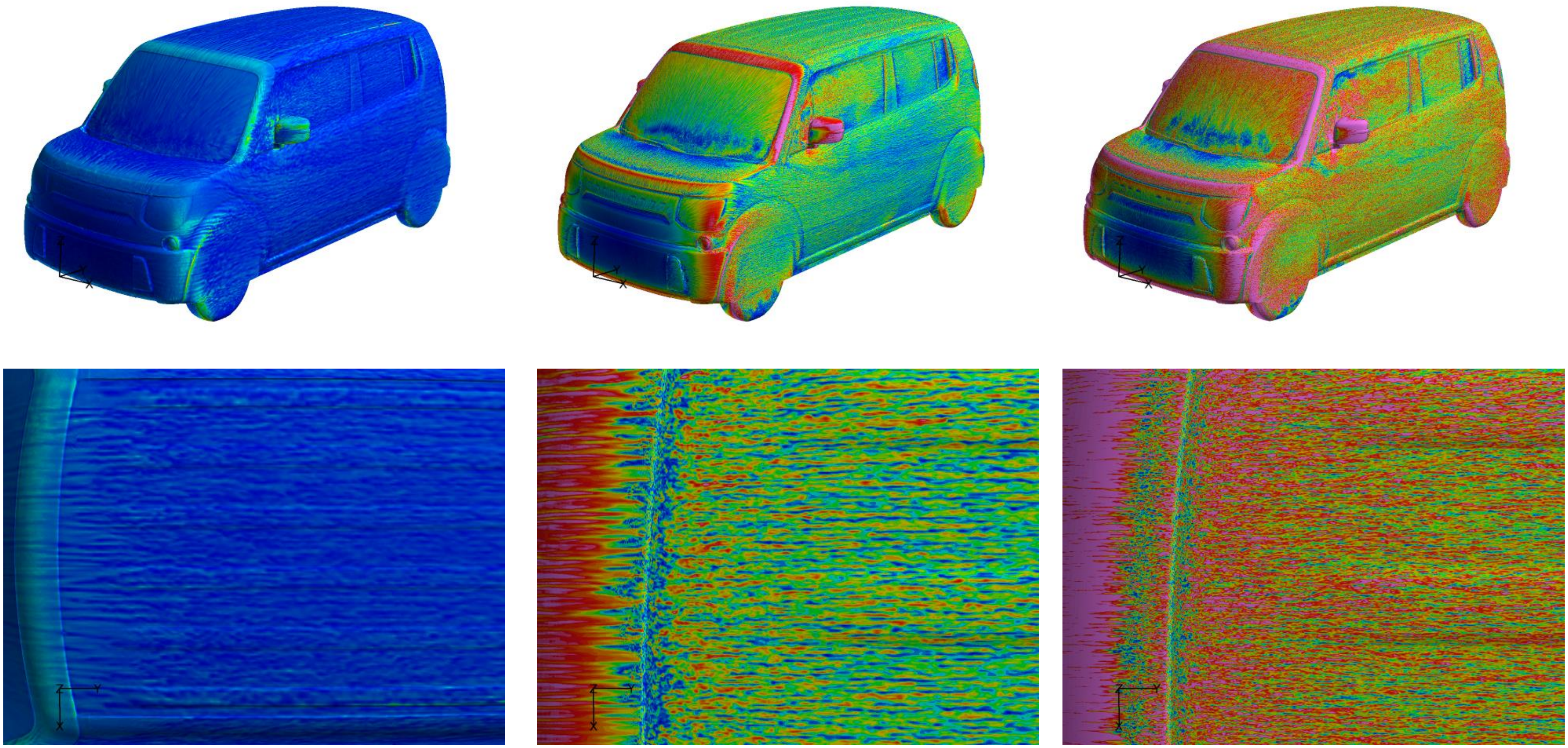
Static Pressure (5 billion mesh)

Ave.

RMS

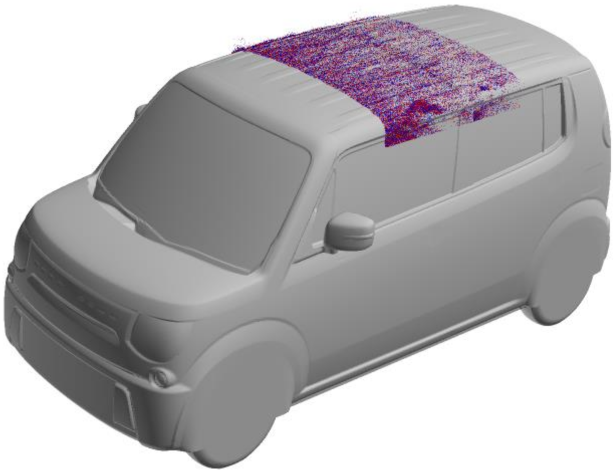


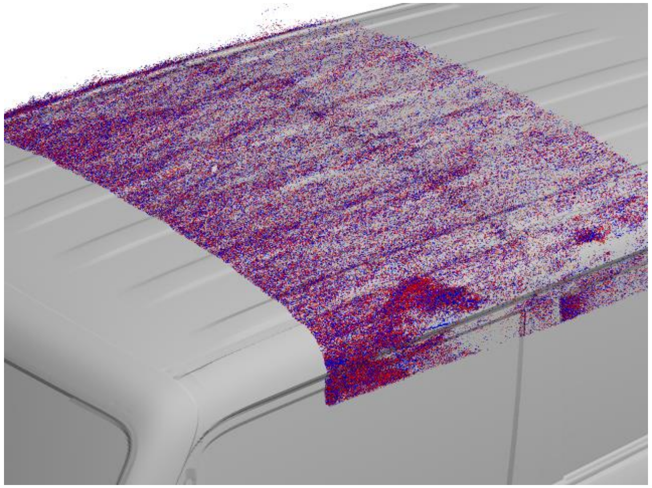
Vortical Structures

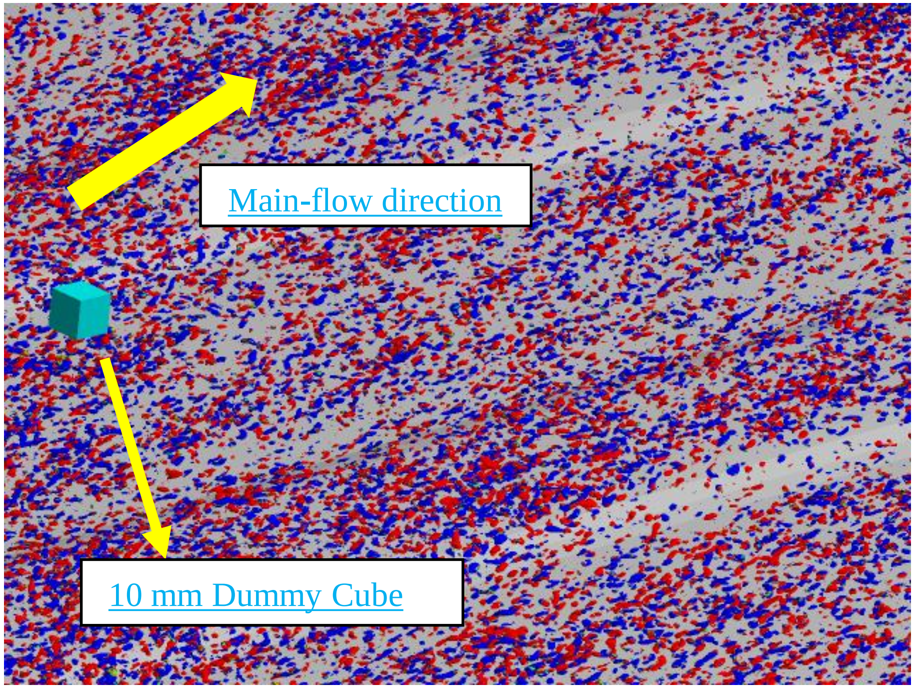


Base Mesh LES 5 Billion Mesh LES 40 Billion Mesh LES

Vortical Structures

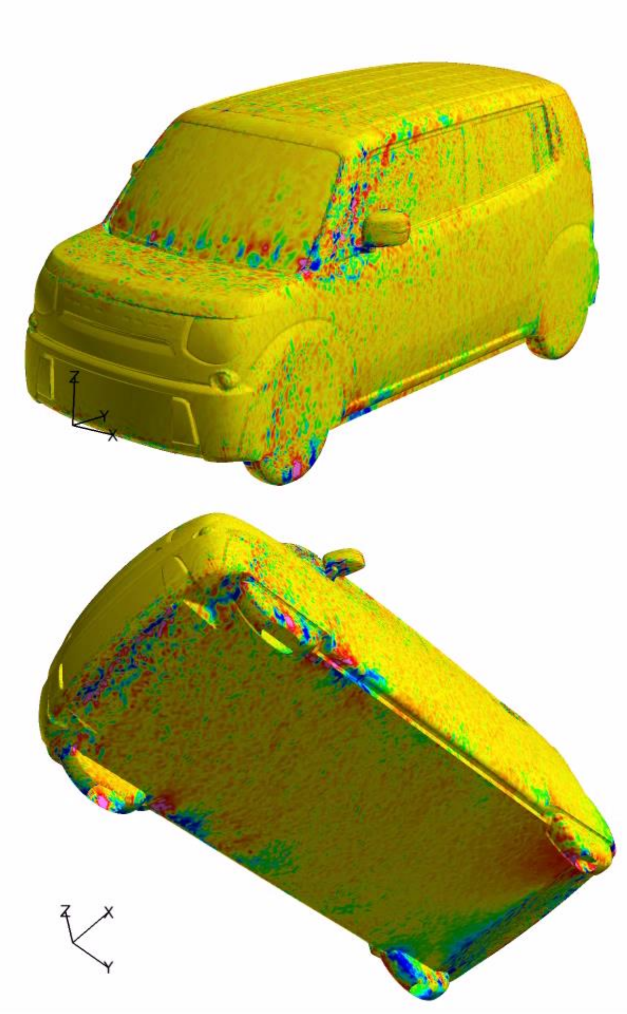




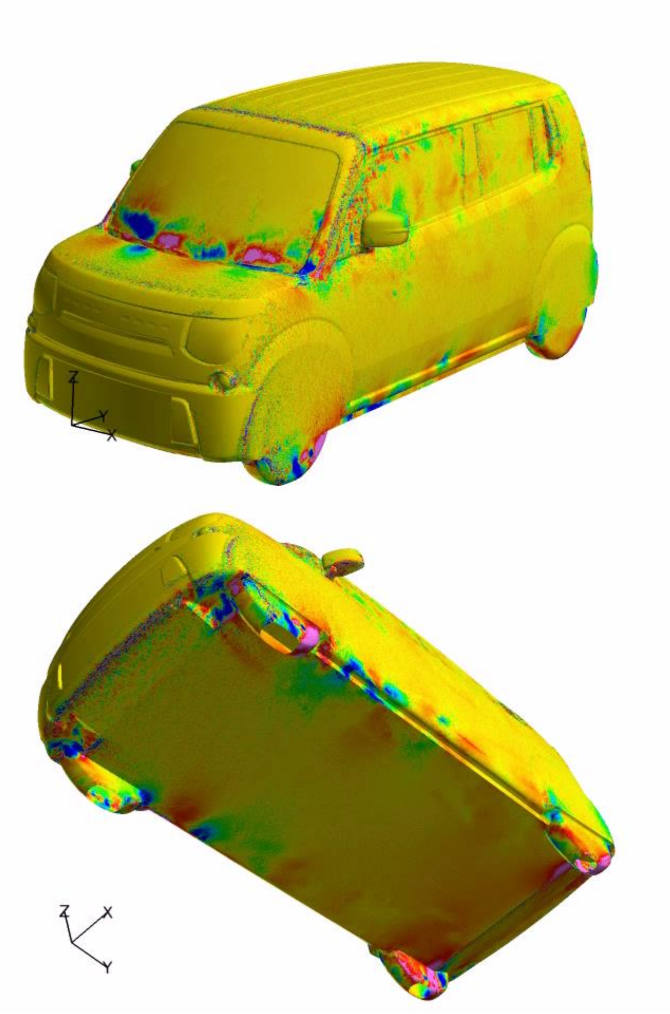


40 Billion Mesh LES

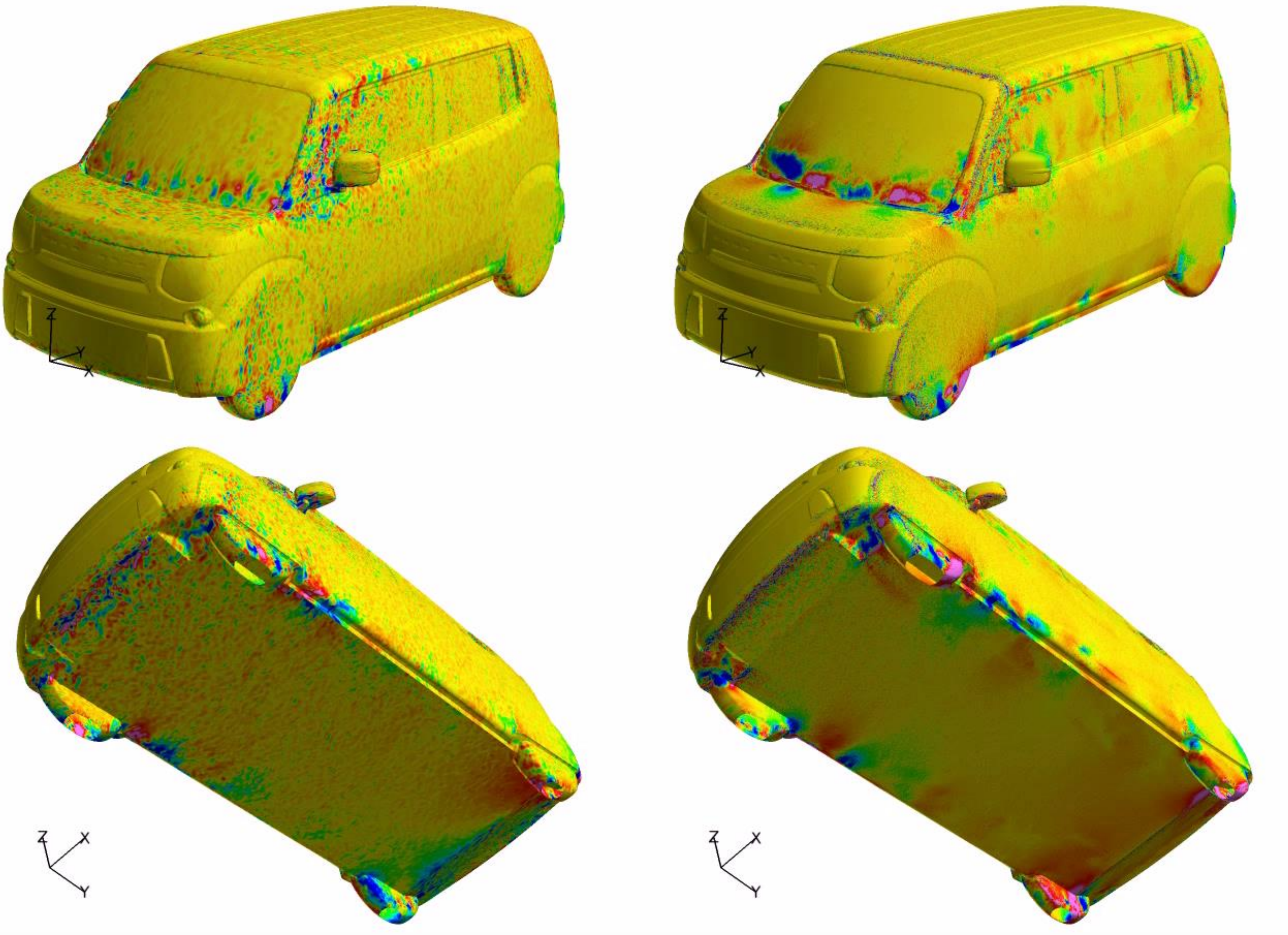
Pressure Fluctuation on the Car Surface (1/3)



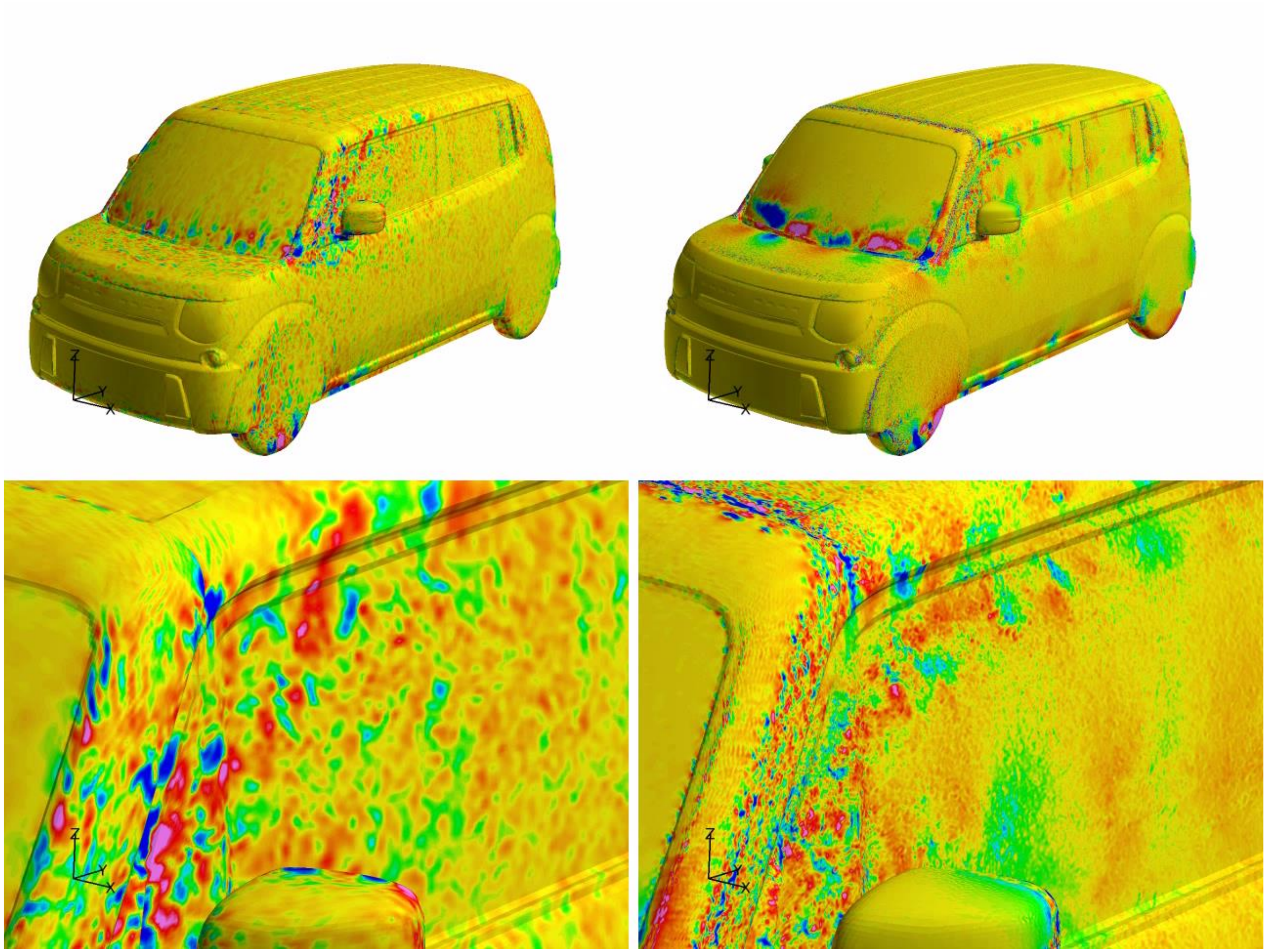
Base Mesh LES



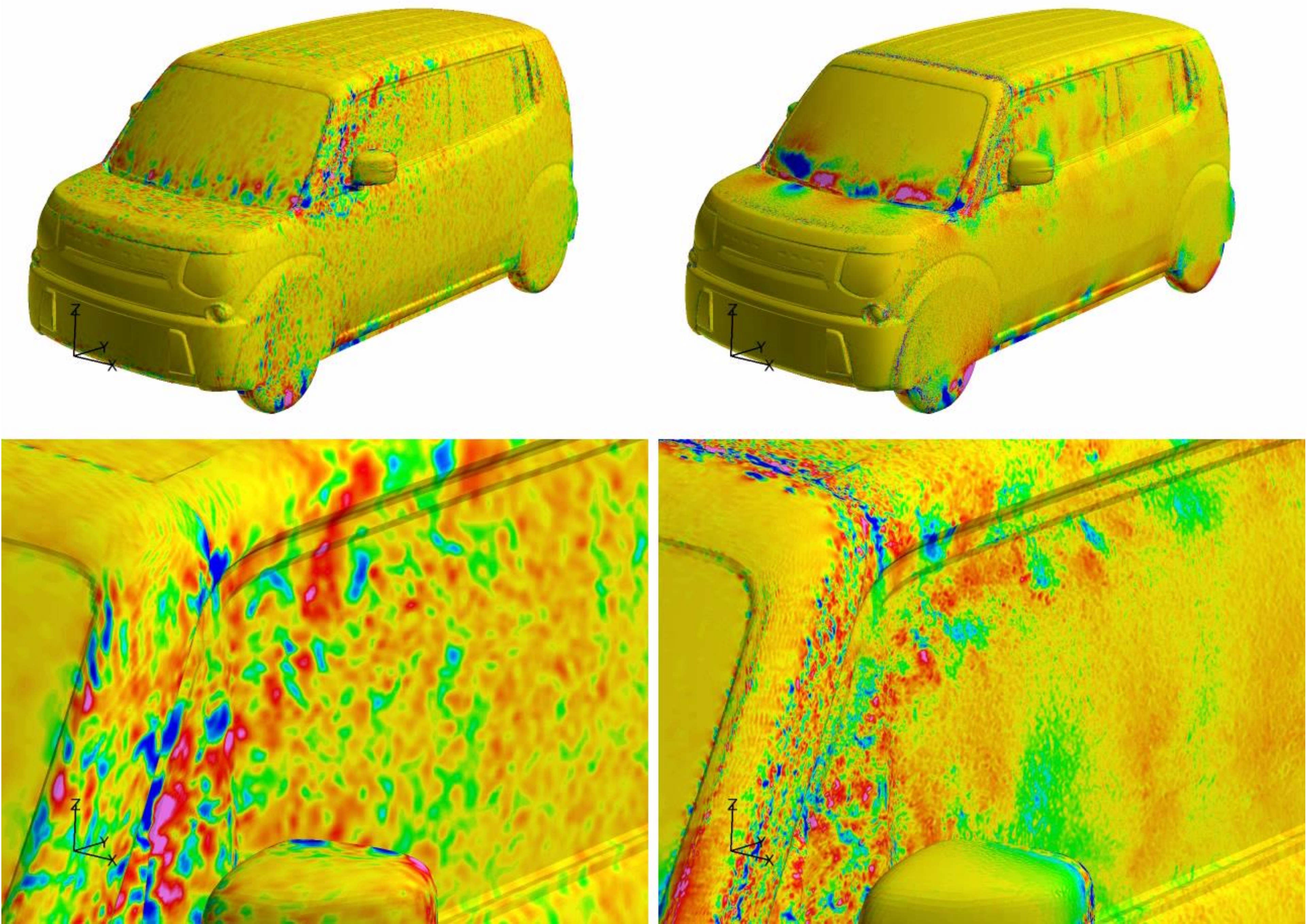
5 Billion Mesh LES


Z
Y
X
Z
Y
X
Z
X
Y
Z
X
Y

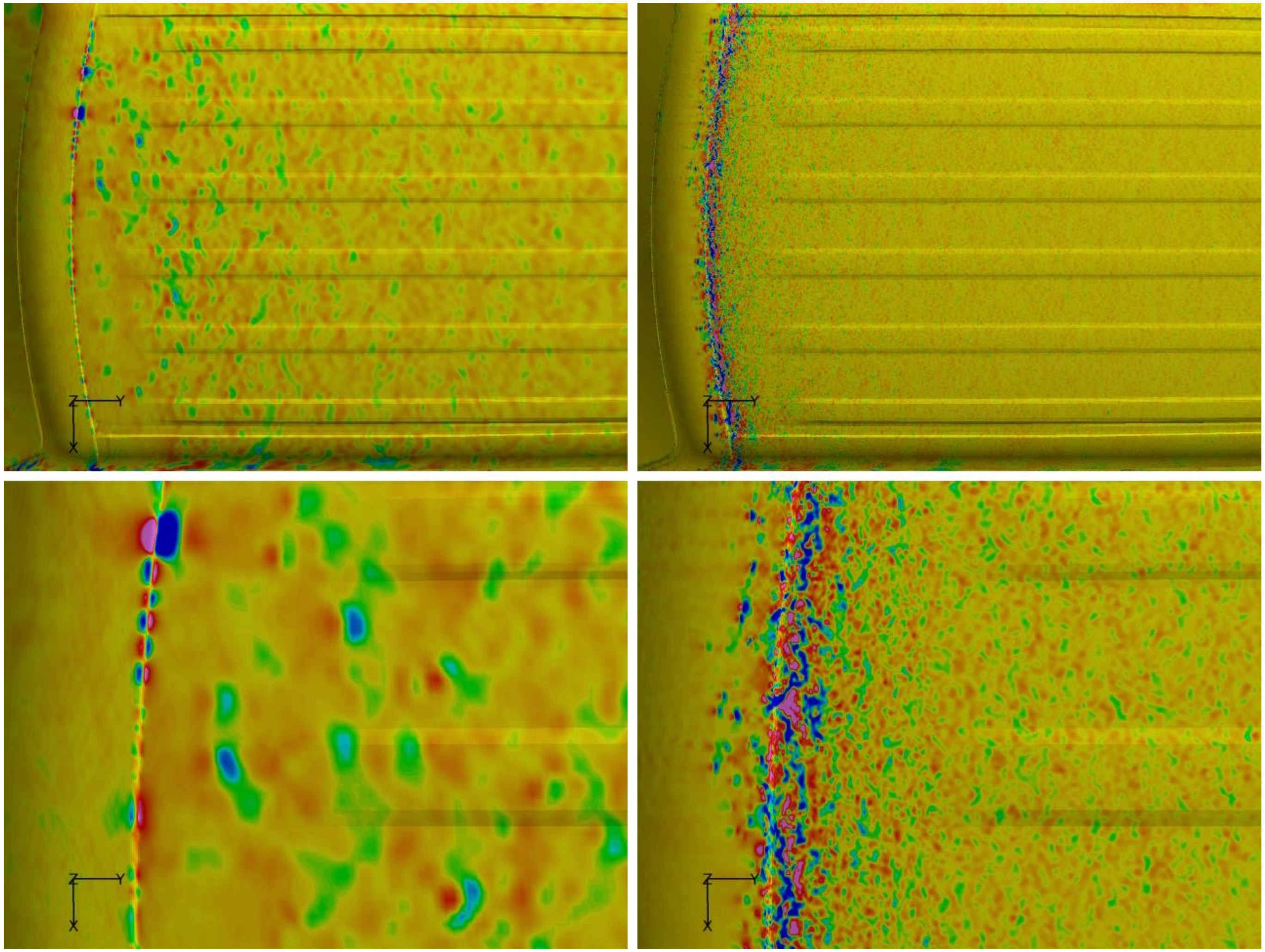
Pressure Fluctuation on the Car Surface (2/3)



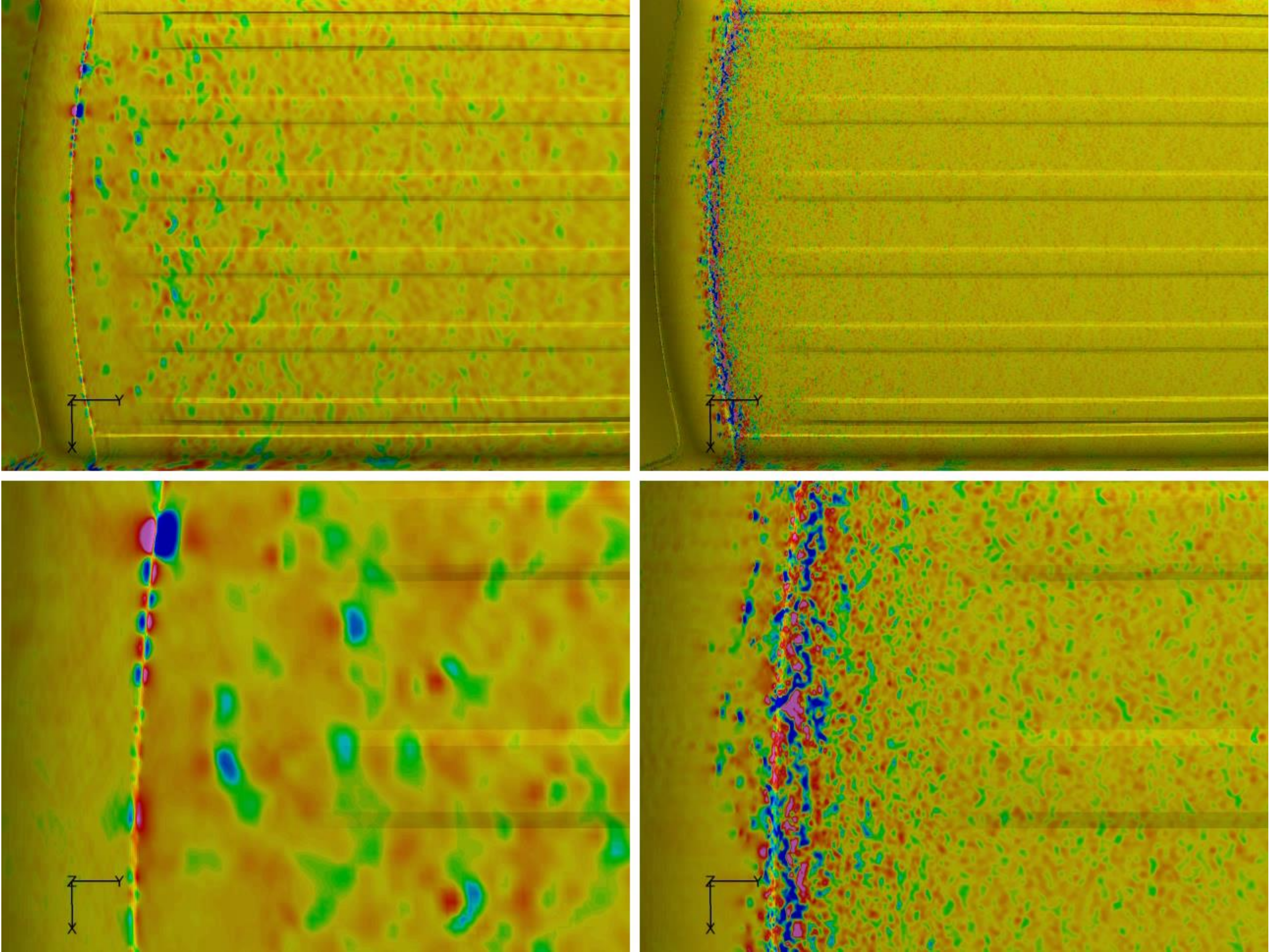
Base Mesh LES　　　　5 Billion Mesh LES


Z
Y
X

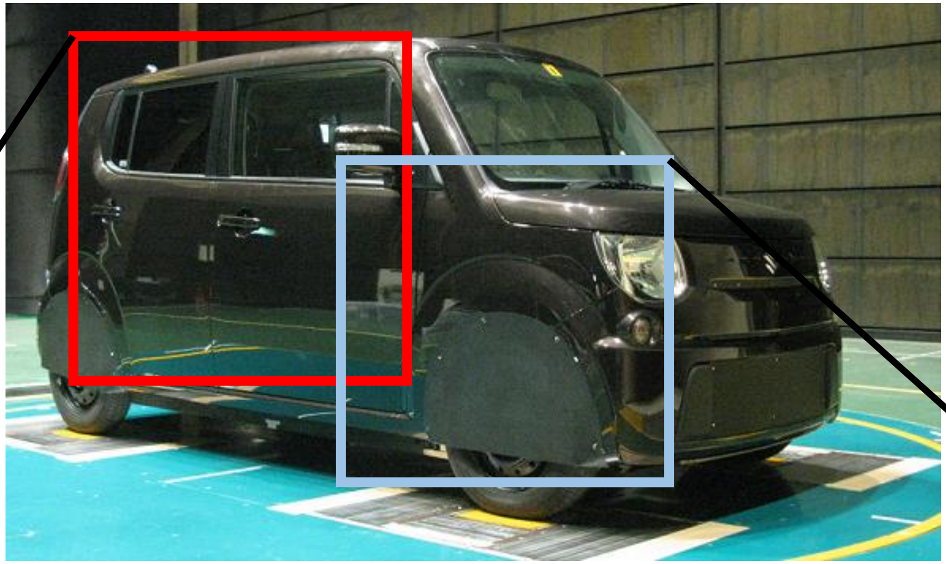
Pressure Fluctuation on the Car Surface (3/3)

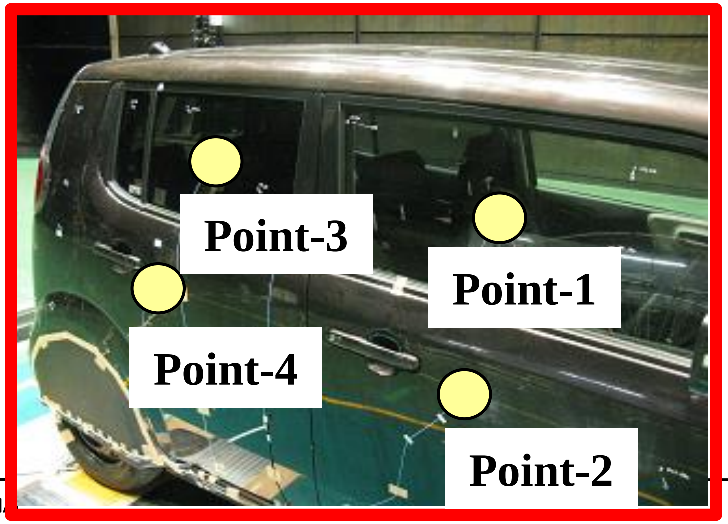


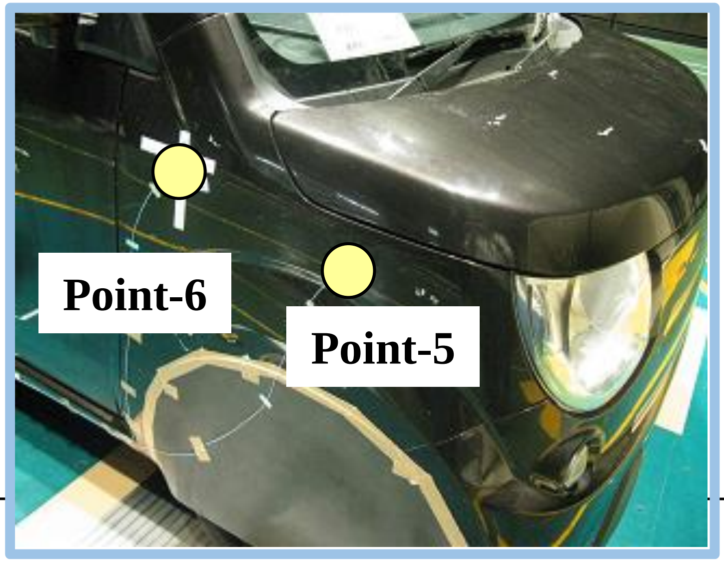
Base Mesh LES　　　　5 Billion Mesh LES


Z Y
X

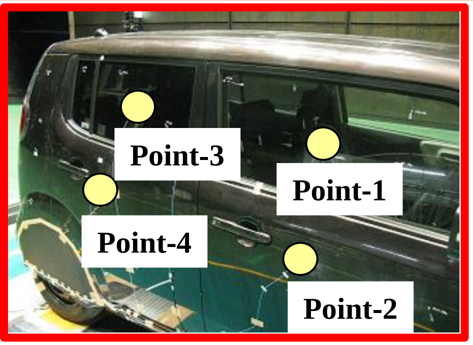
Sampling points of pressure fluctuation

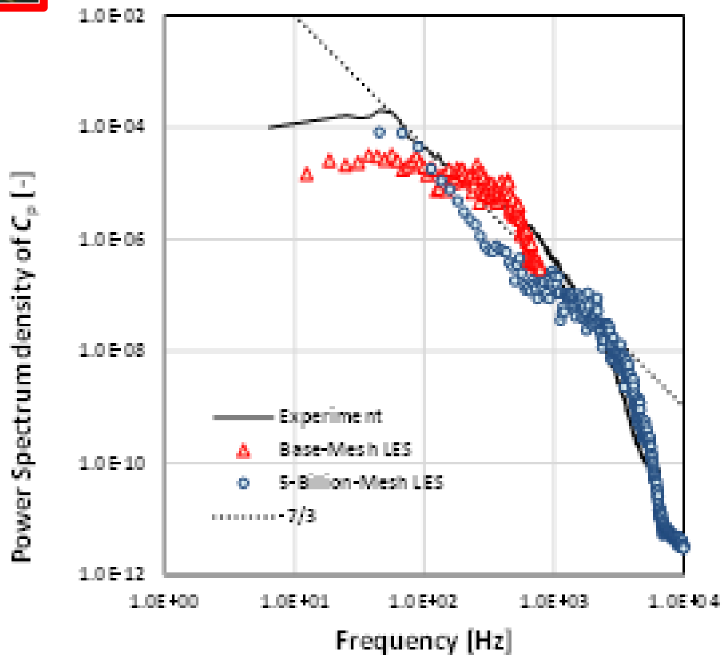




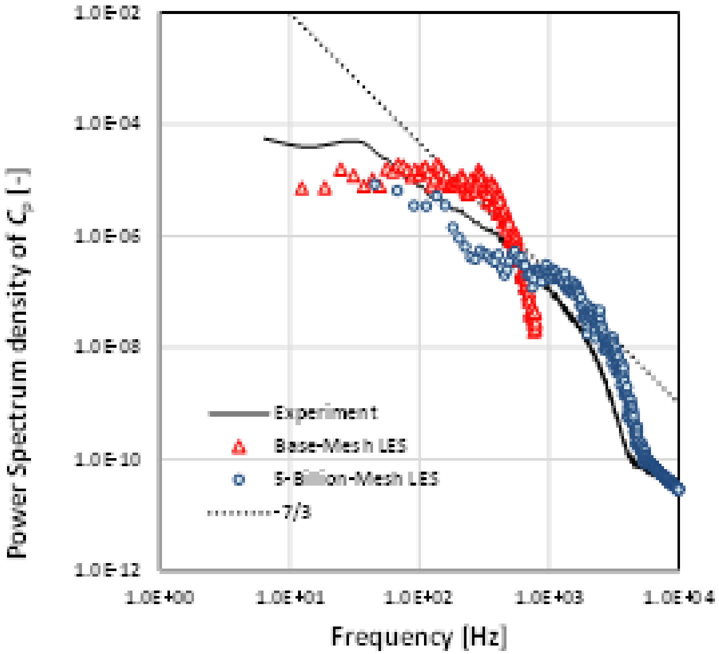


Power Spectrum of Pressure Fluctuation (1/3)



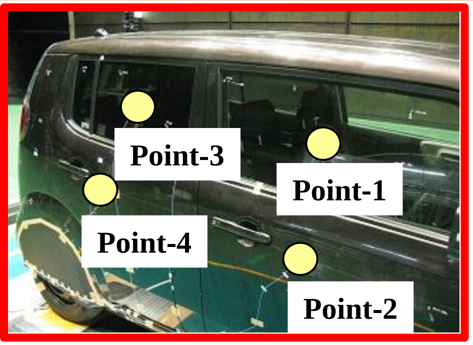


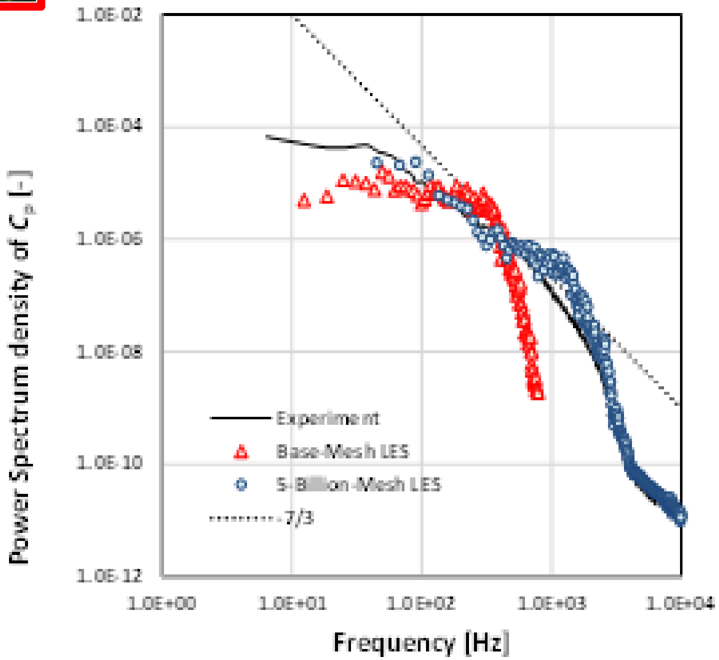
Point-1



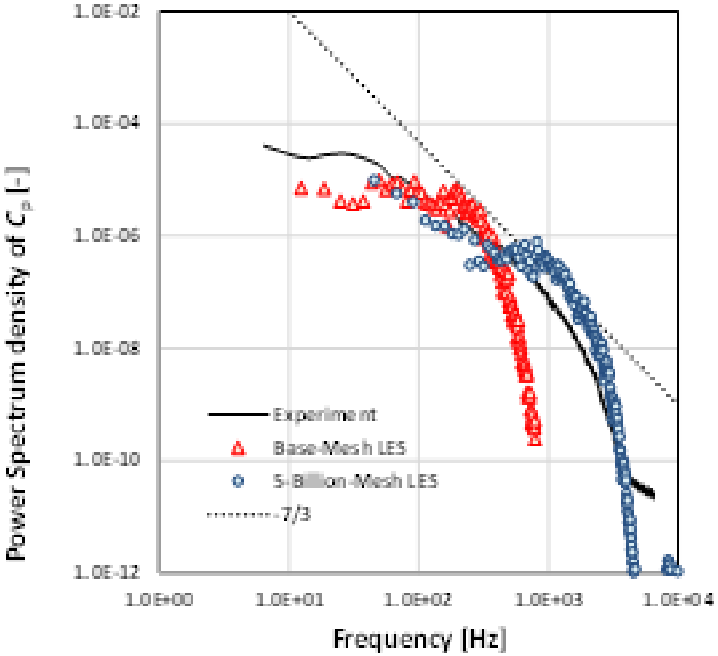
Point-2

Power Spectrum of Pressure Fluctuation (2/3)



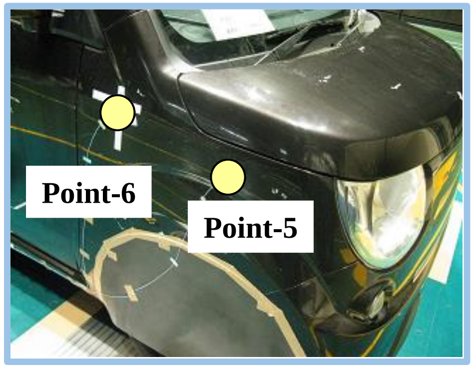


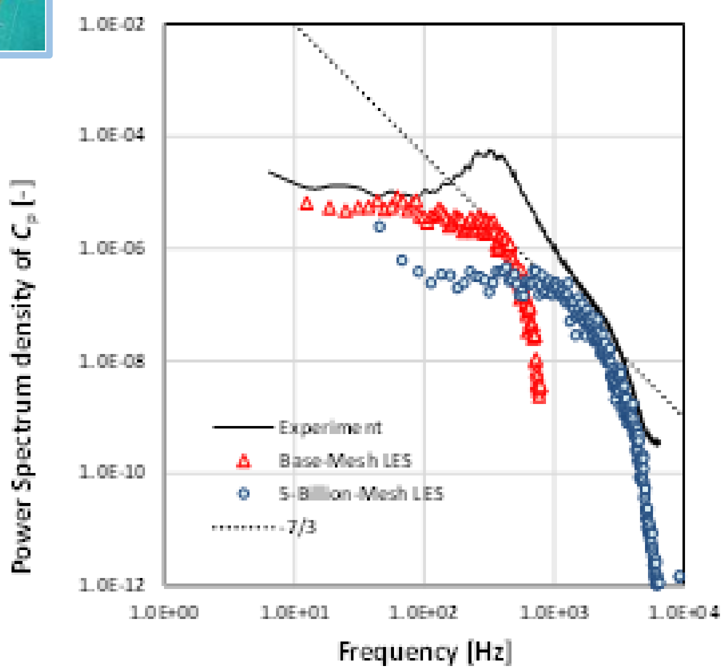
Point-3



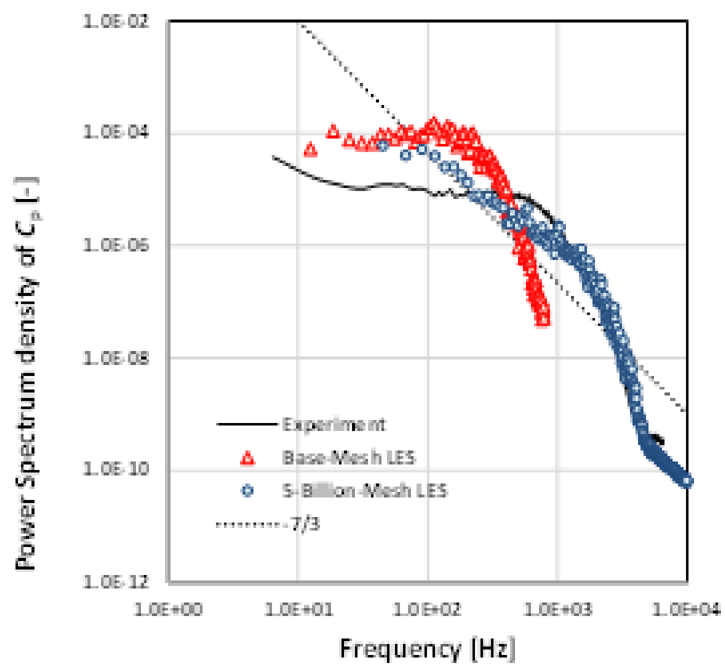
Point-4

Power Spectrum of Pressure Fluctuation (3/3)



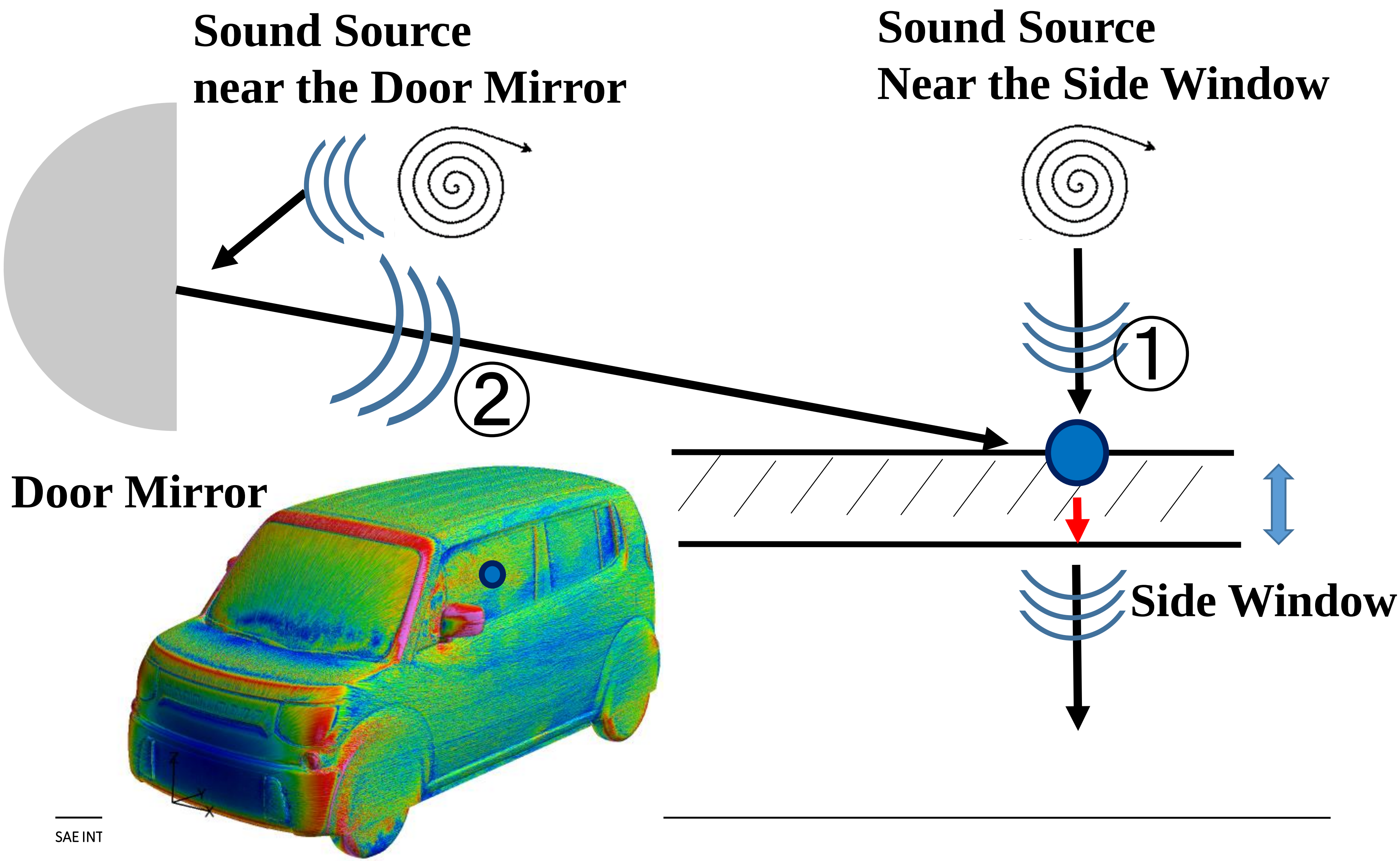


Point-5

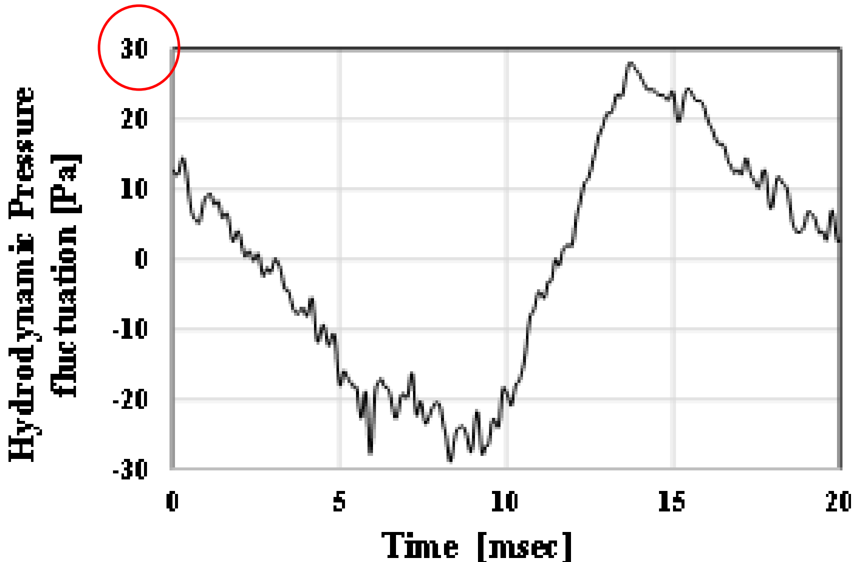


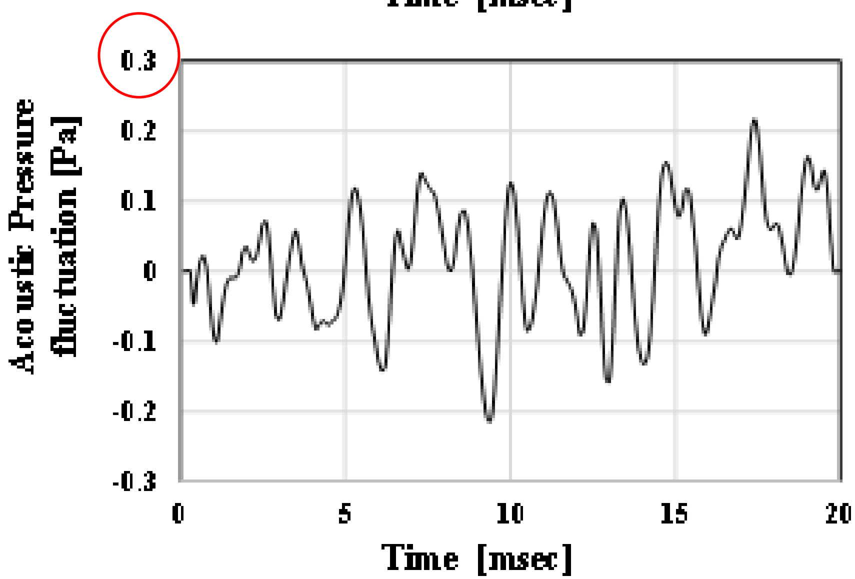
Point-6

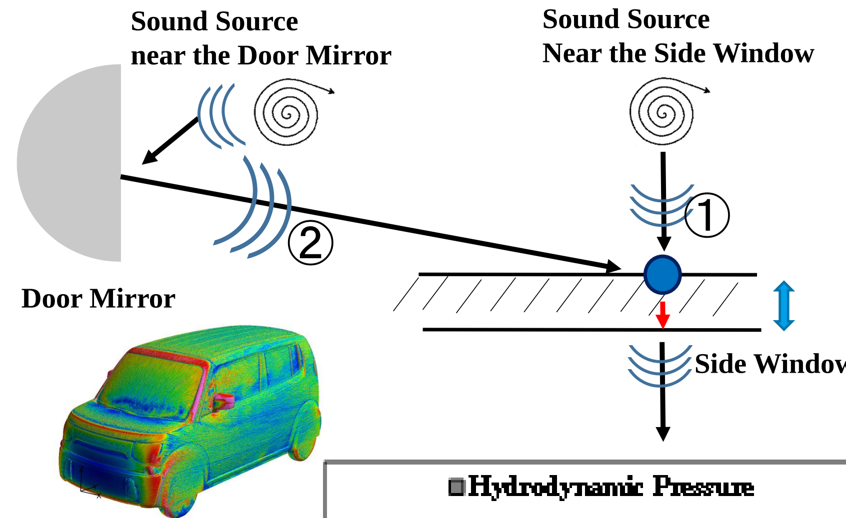
Acoustic and Hydrodynamics Pressure Fluctuation (1/2)

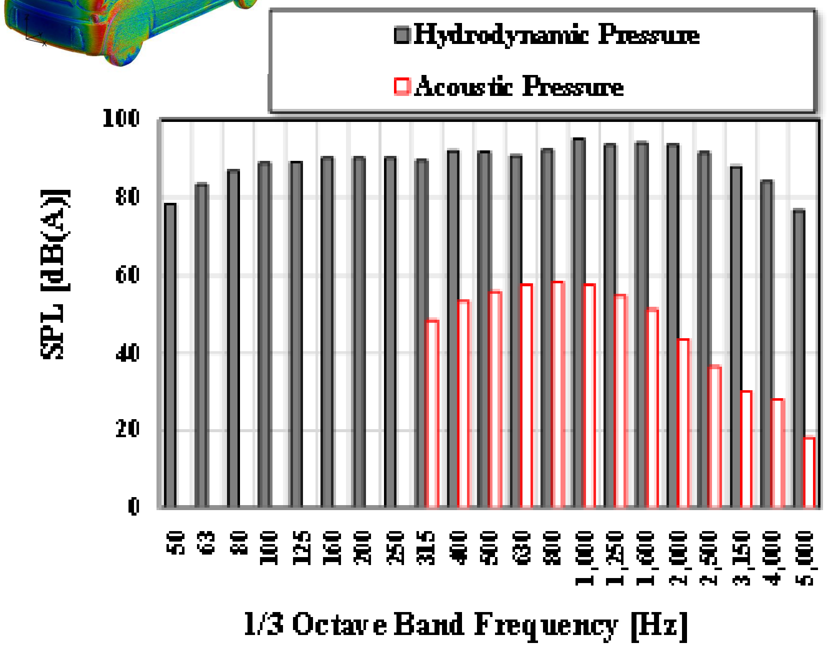


Acoustic and Hydrodynamics Pressure Fluctuation (2/2)





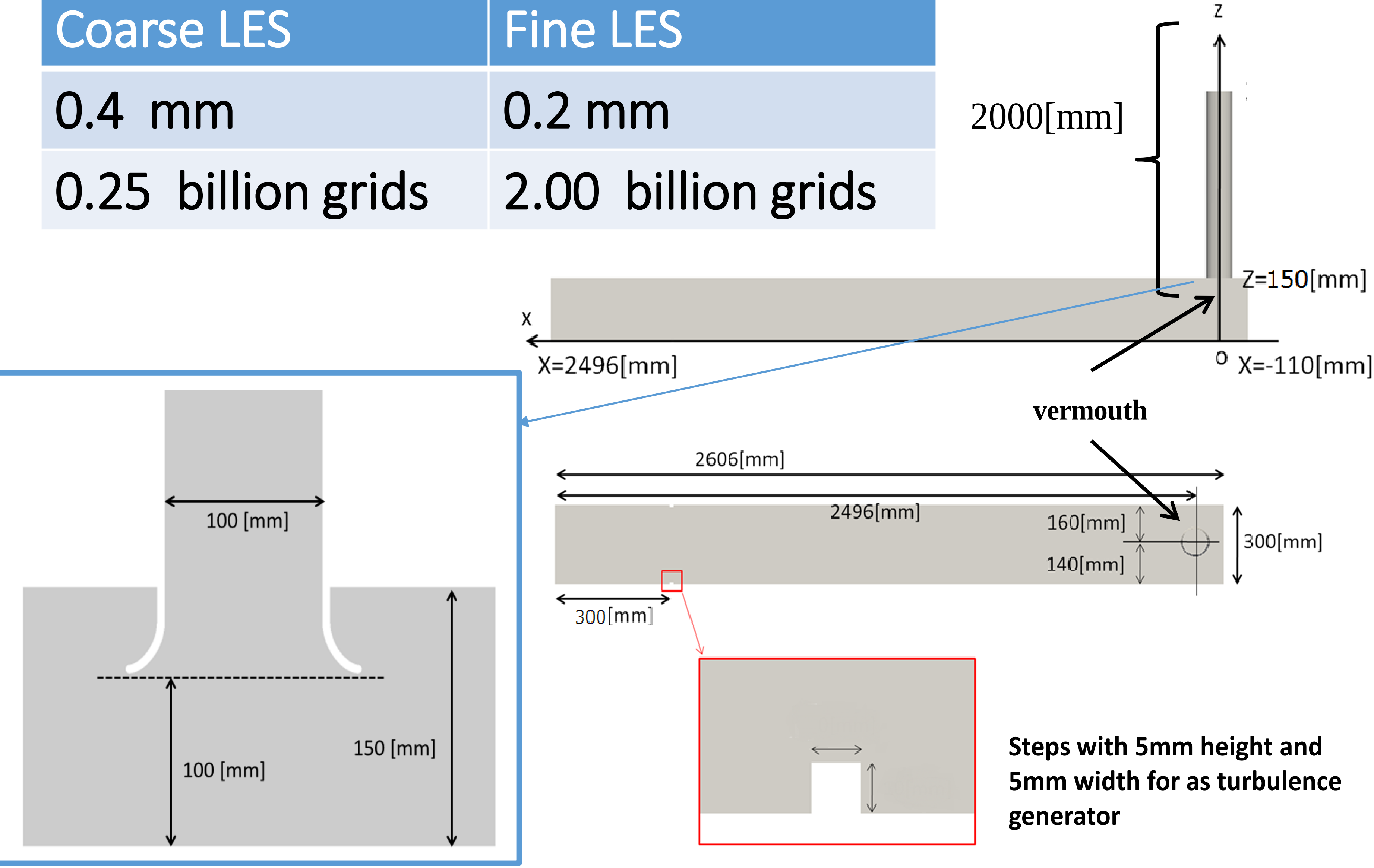




2.3 準直接計算の工学応用3
ポンプ吸込水槽の
吸込み渦発生メカニズム

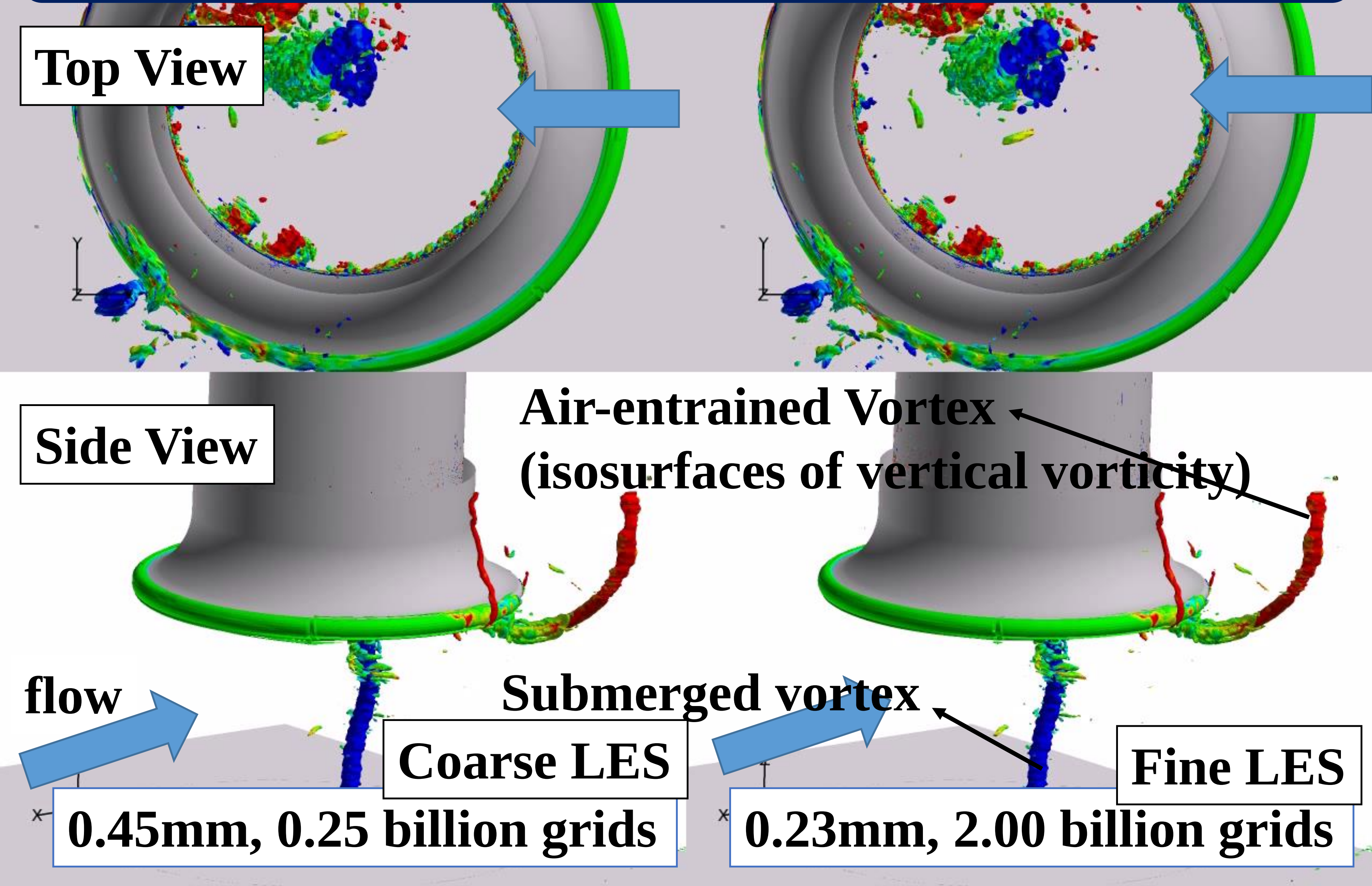
Numerical Conditions

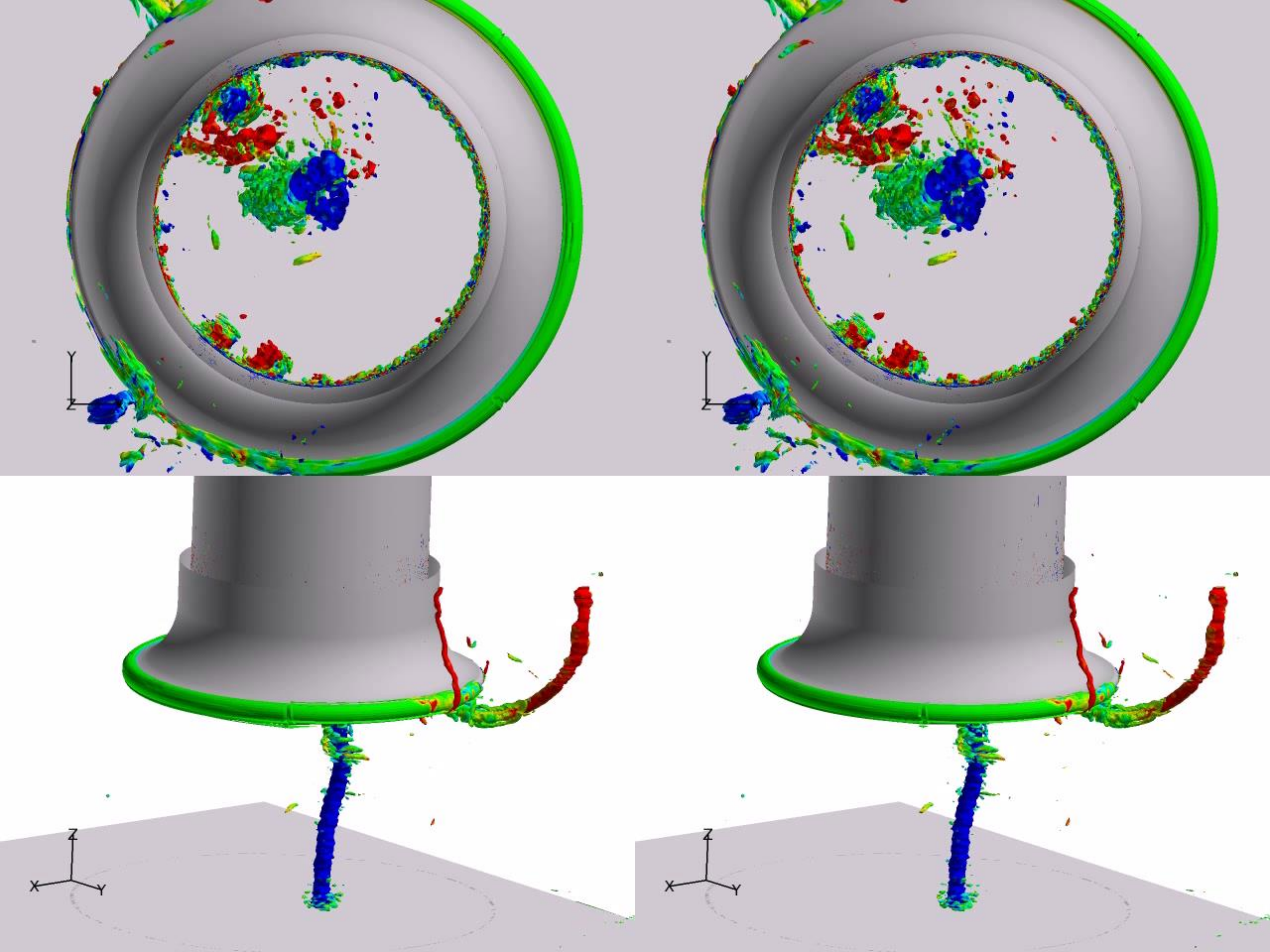
Coarse LES	Fine LES
0.4 mm	0.2 mm
0.25 billion grids	2.00 billion grids



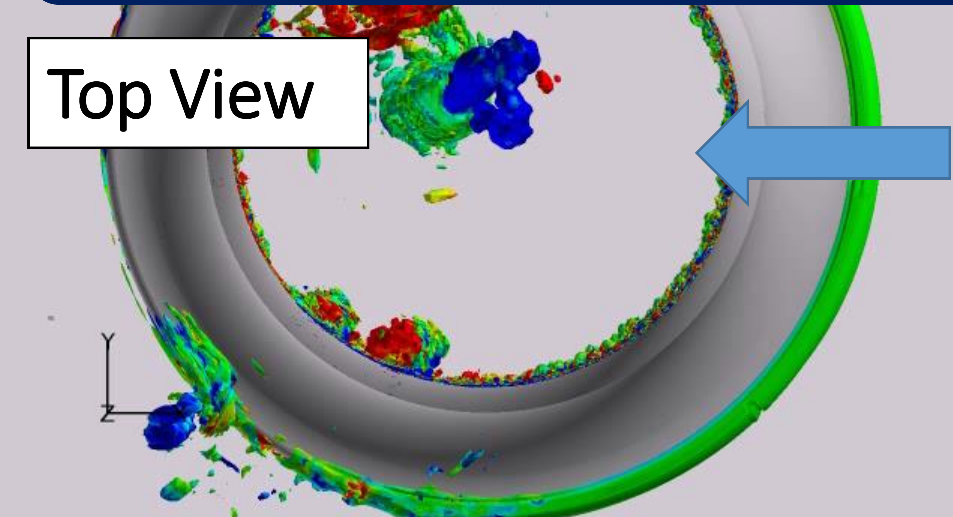
Steps with 5mm height and 5mm width for as turbulence generator

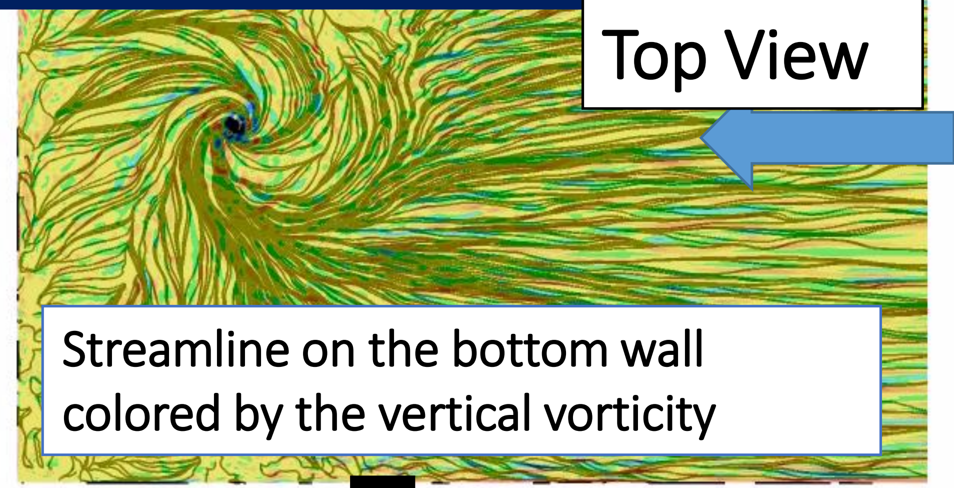
Grid Resolutions Dependency

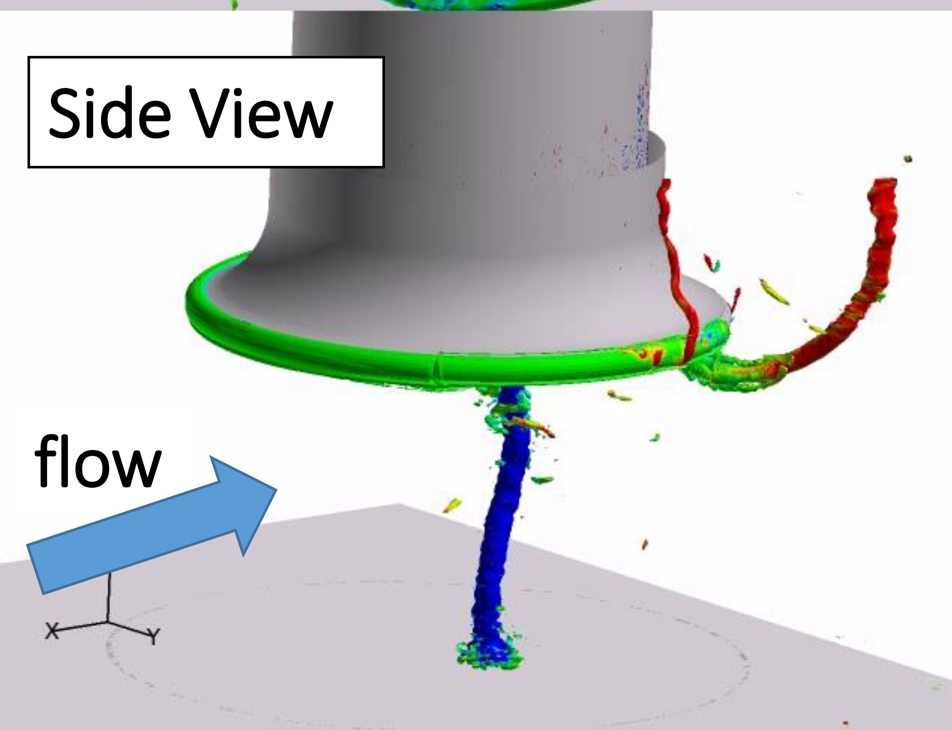


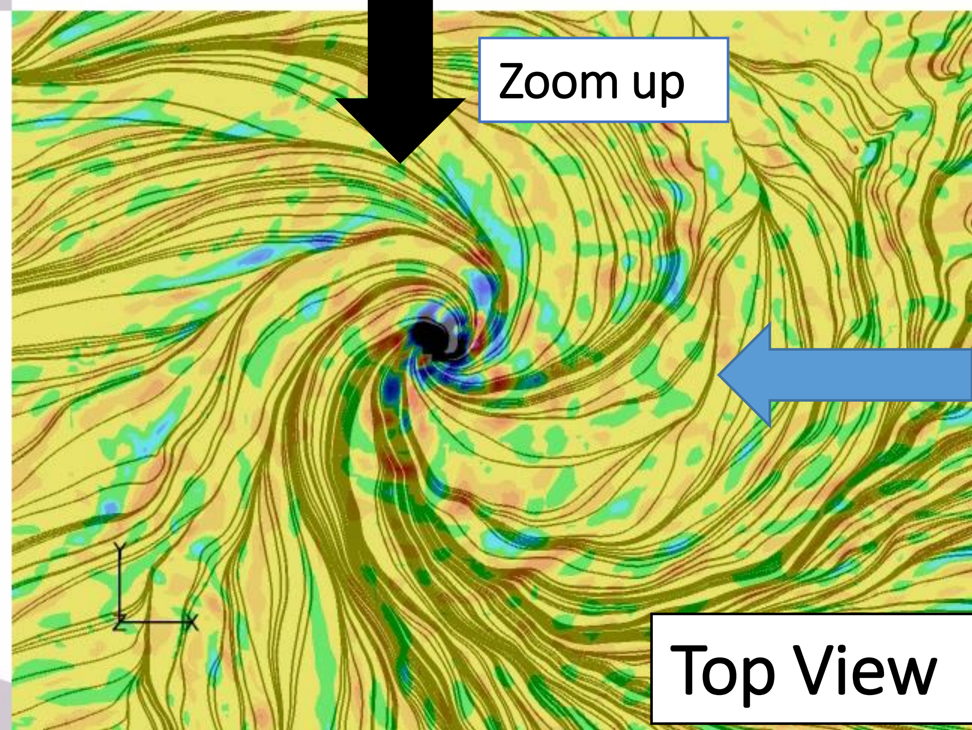

Y
Z
Y
Z
Z
X
Y
Z
X
Y

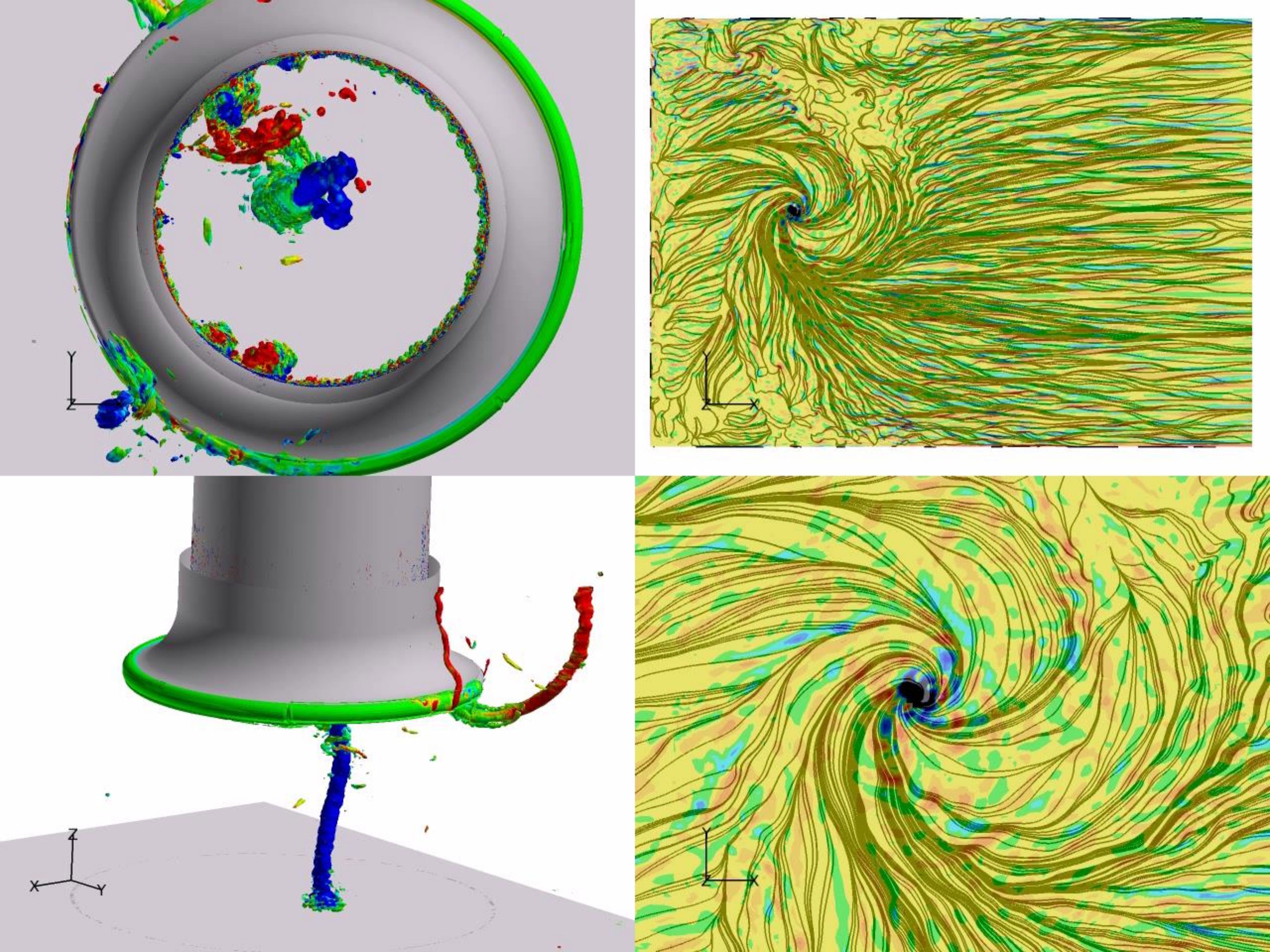
Appearance and Disappearance







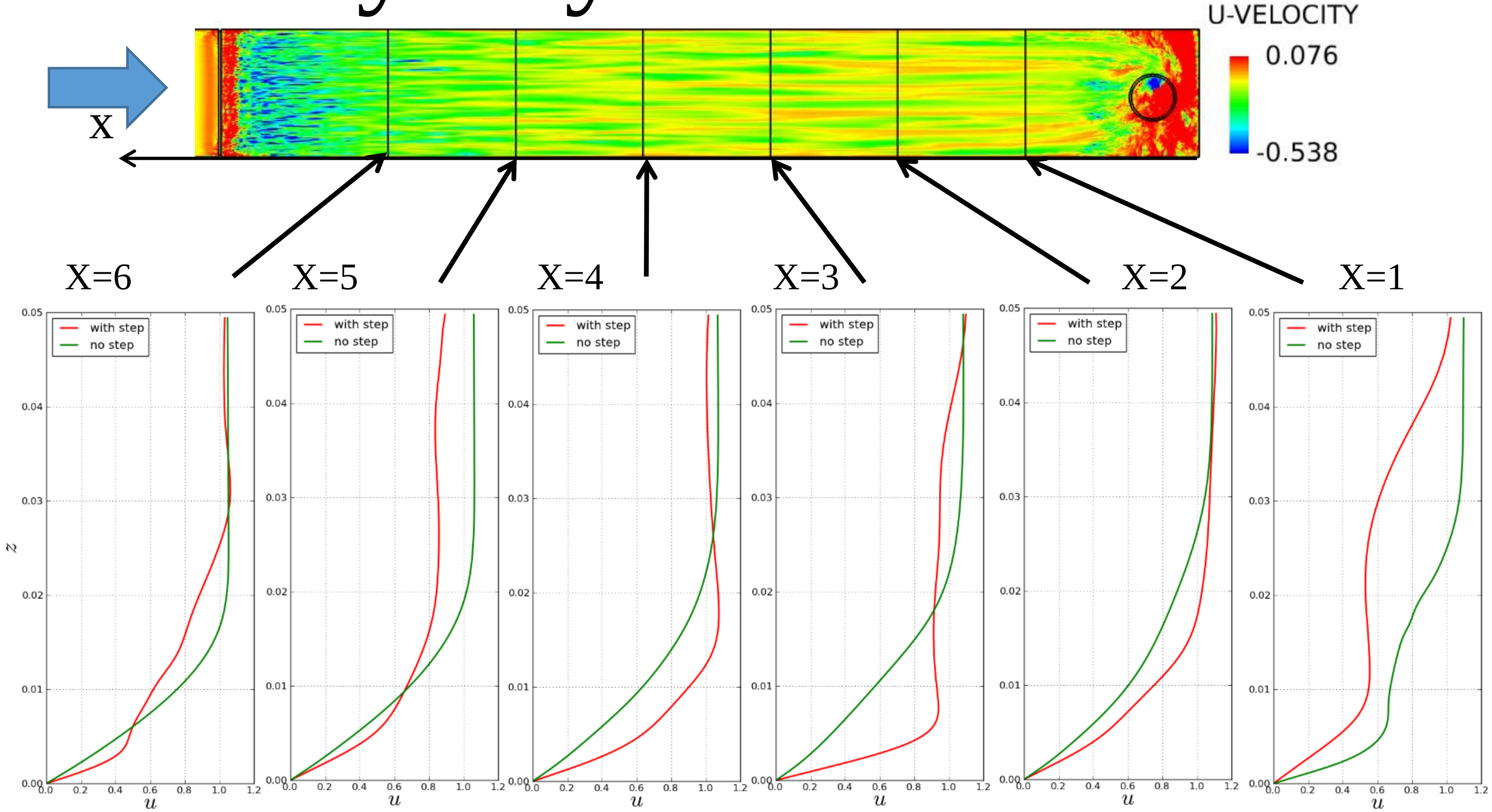




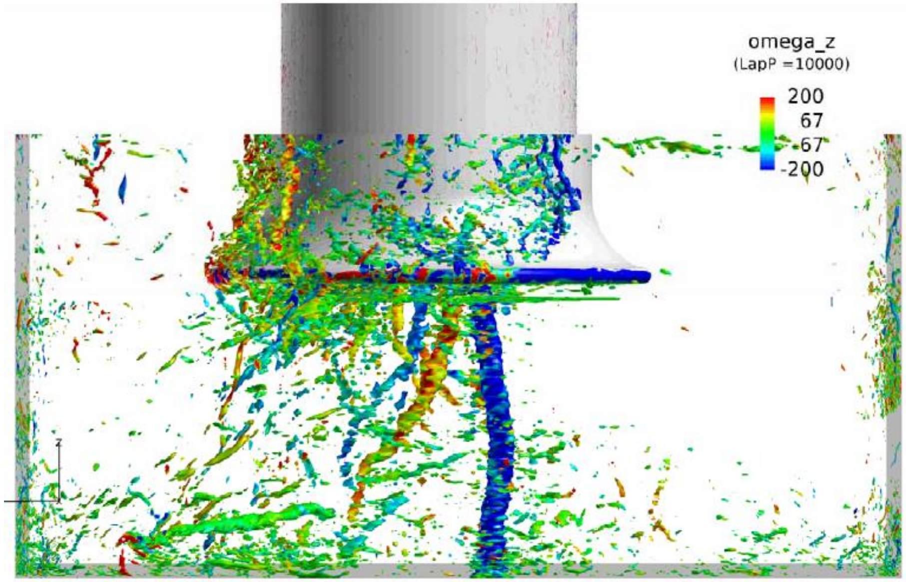
Y
Z
X

Approaching Boundary Layer

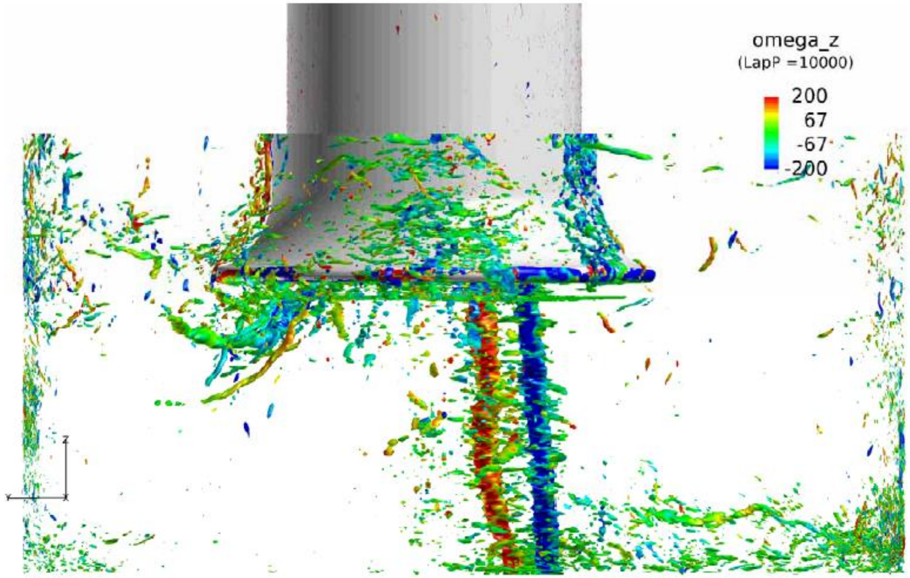
- Turbulent Boundary Layer
- Laminar Boundary Layer
- No Boundary Layer



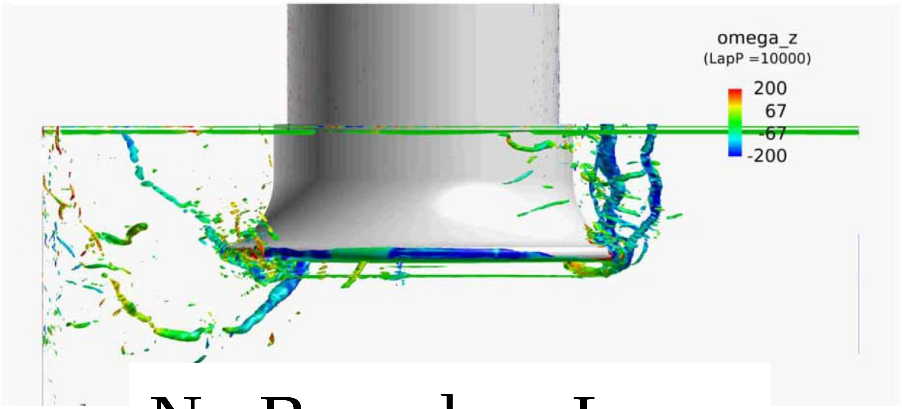
Approaching Boundary Layer



Turbulent Boundary Layer



Laminar Boundary Layer

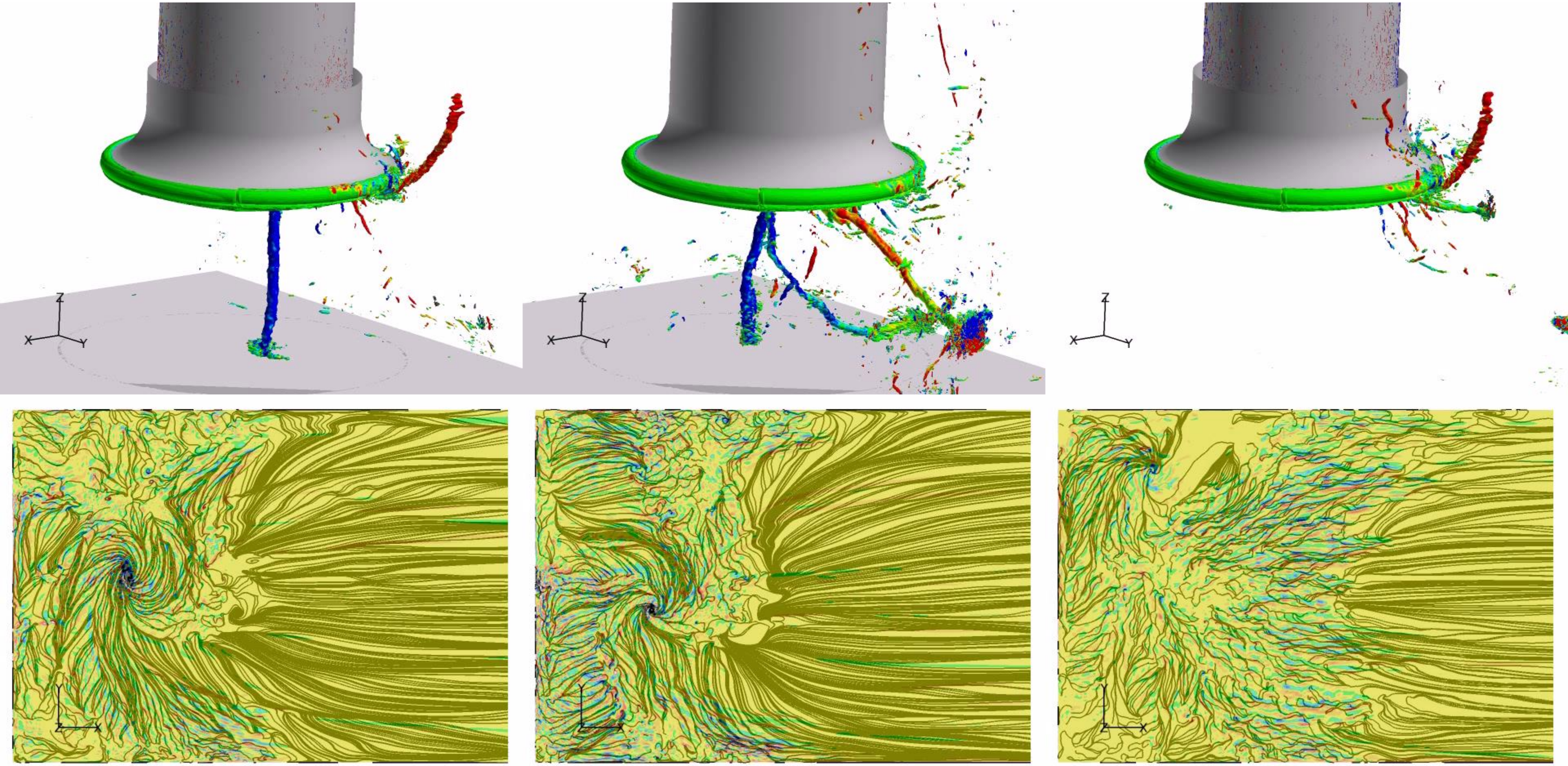


No Boundary Layer

Summary of Case-1

- Vortex Appearance
  - ✓ Velocity shear of approaching B. L.
  - ✓ Small vortices in TBL are not origin.
- Vortex Disappearance
  - ✓ Merging of vortices

現象の理解に基づく吸込渦抑制対策

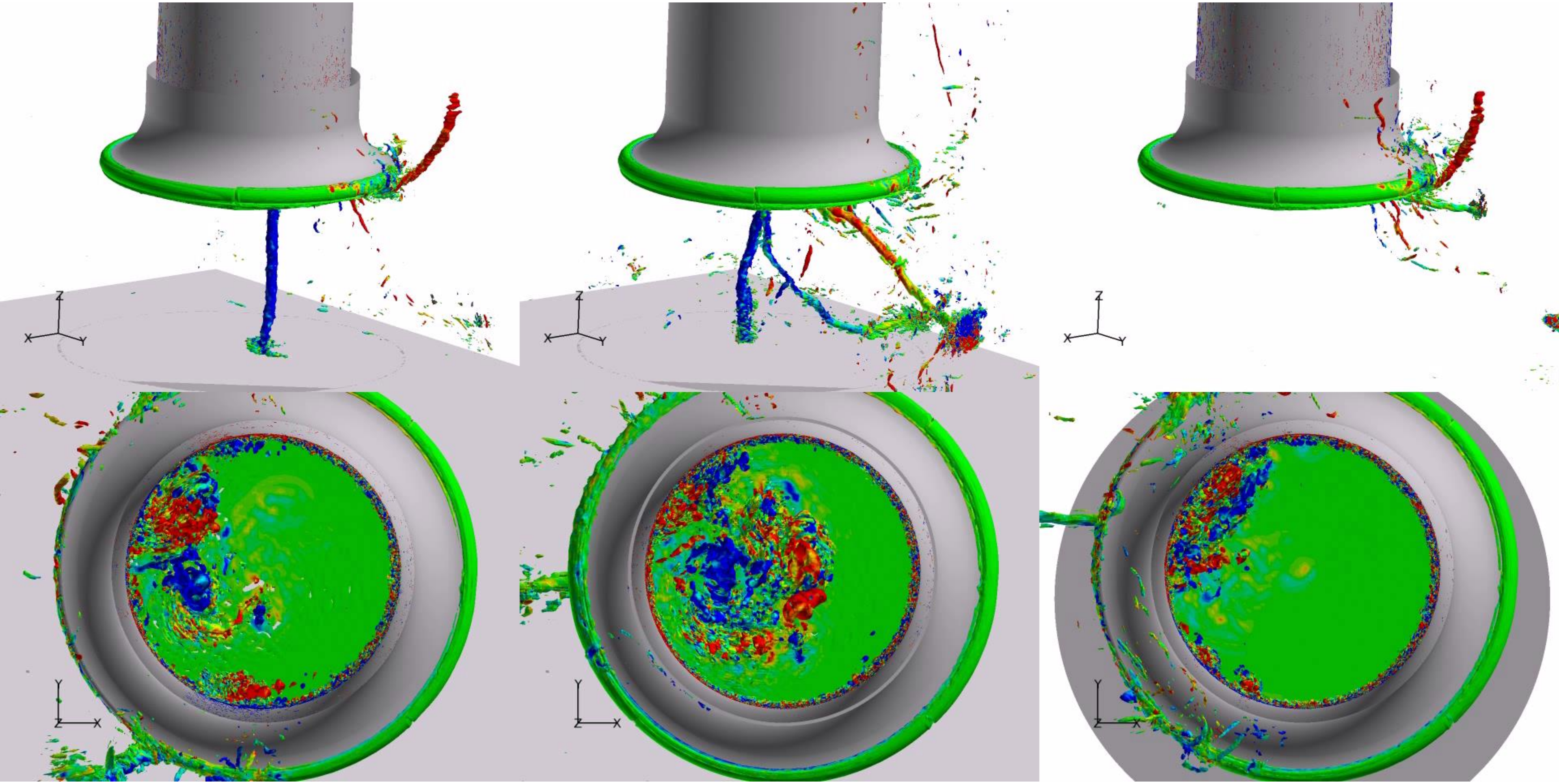


標準

対策1:
水深を高くする。

対策2:
水槽を深くする。

現象の理解に基づく吸込渦抑制対策



標準

対策1:
水深を高くする。

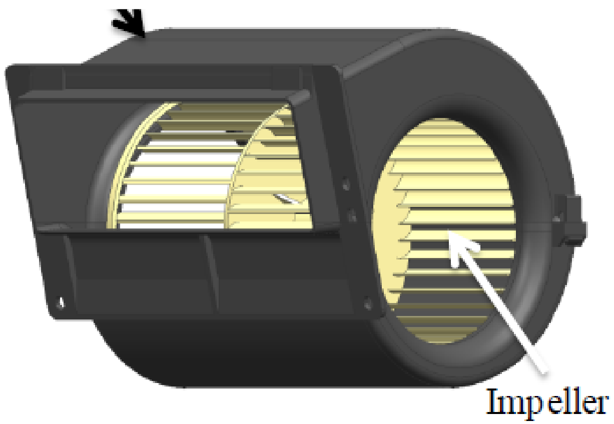
対策2:
水槽を深くする。

2.4 準直接計算の工学応用2
遠心送風機から発生する
空力騒音の予測

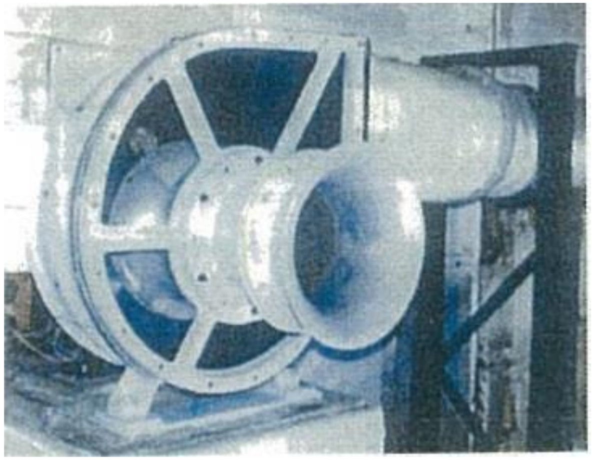
INTRODUCTION

Background & Objective

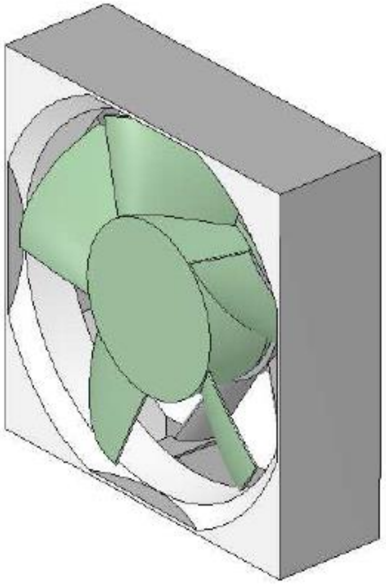
- Accurate prediction of aeroacoustics noise from a blower or fan
- Validation studies for several kind of blowers and fan



Ref. **AICFM13-023**



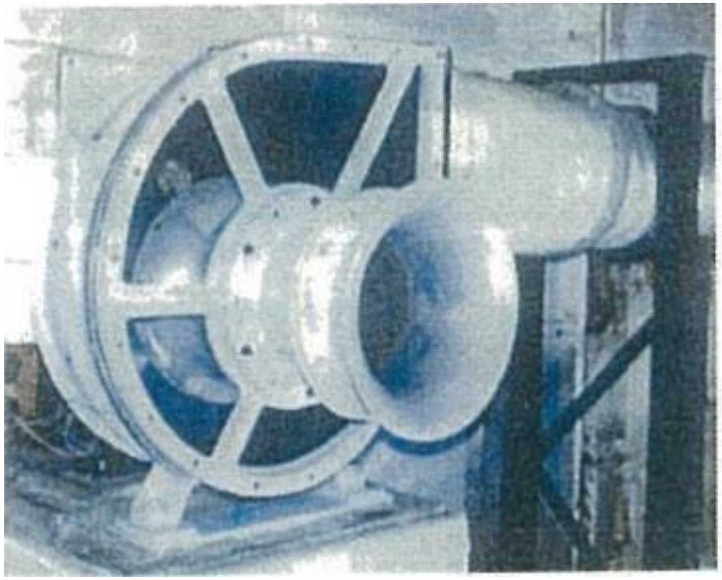
AICFM13-139

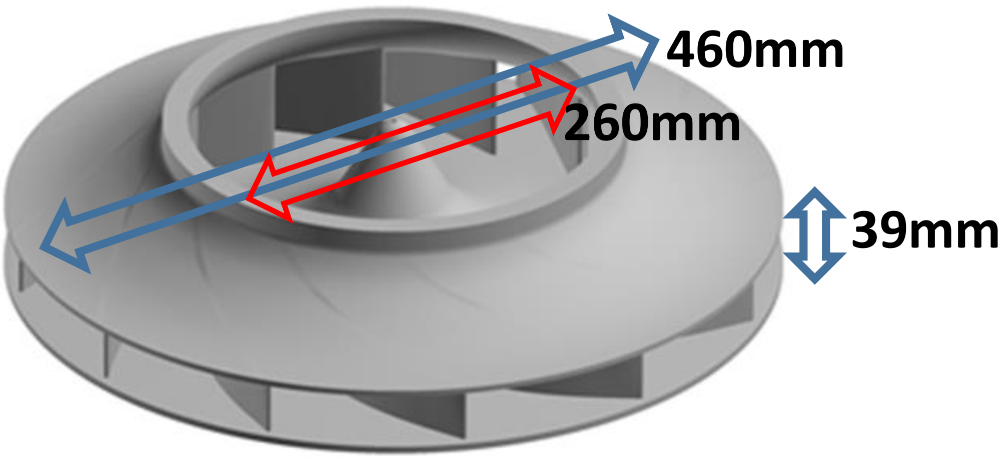


Ref. **AICFM13-097**

Test Centrifugal Blower

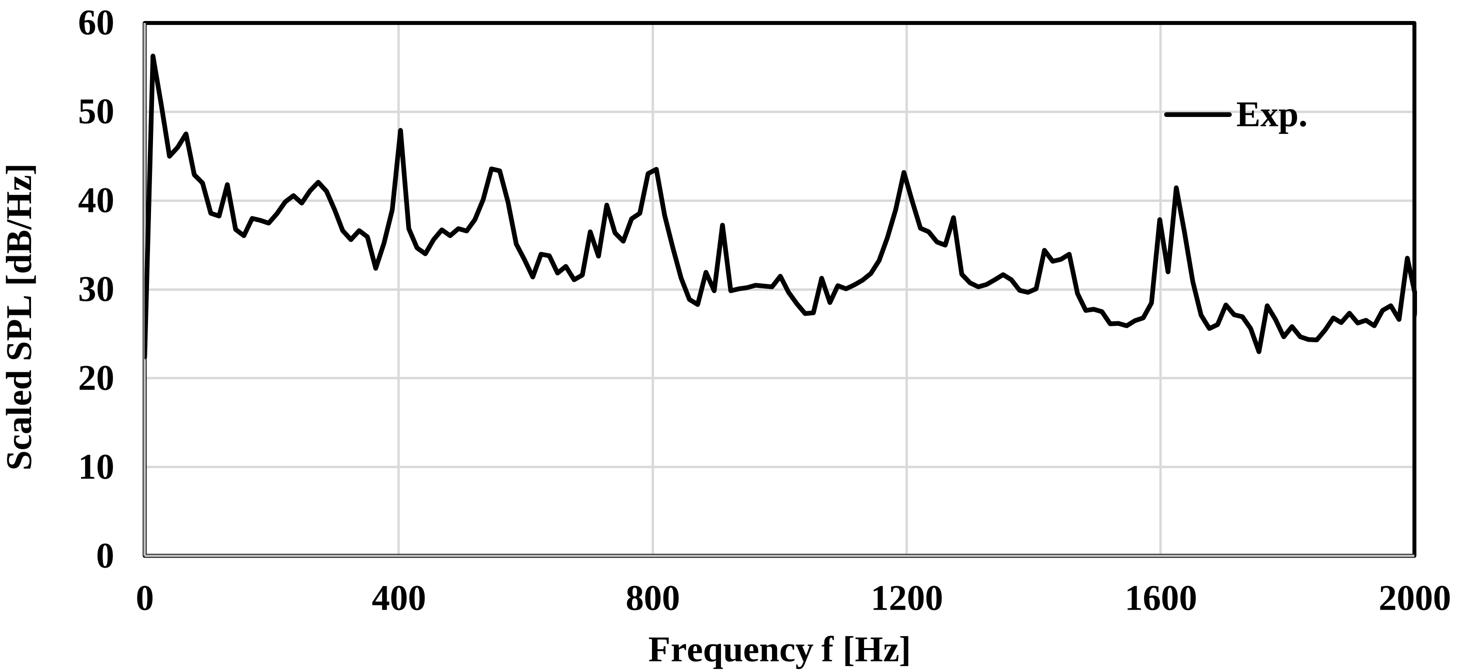
Number of impeller blades	**12**
Diameter at inlet	**260 [mm]**
Diameter at outlet	**460 [mm]**
Outlet height	**39 [mm]**
Blade profile	**NACA65**
Revolution speed	**2,000 ~ 3,000 [rpm]**





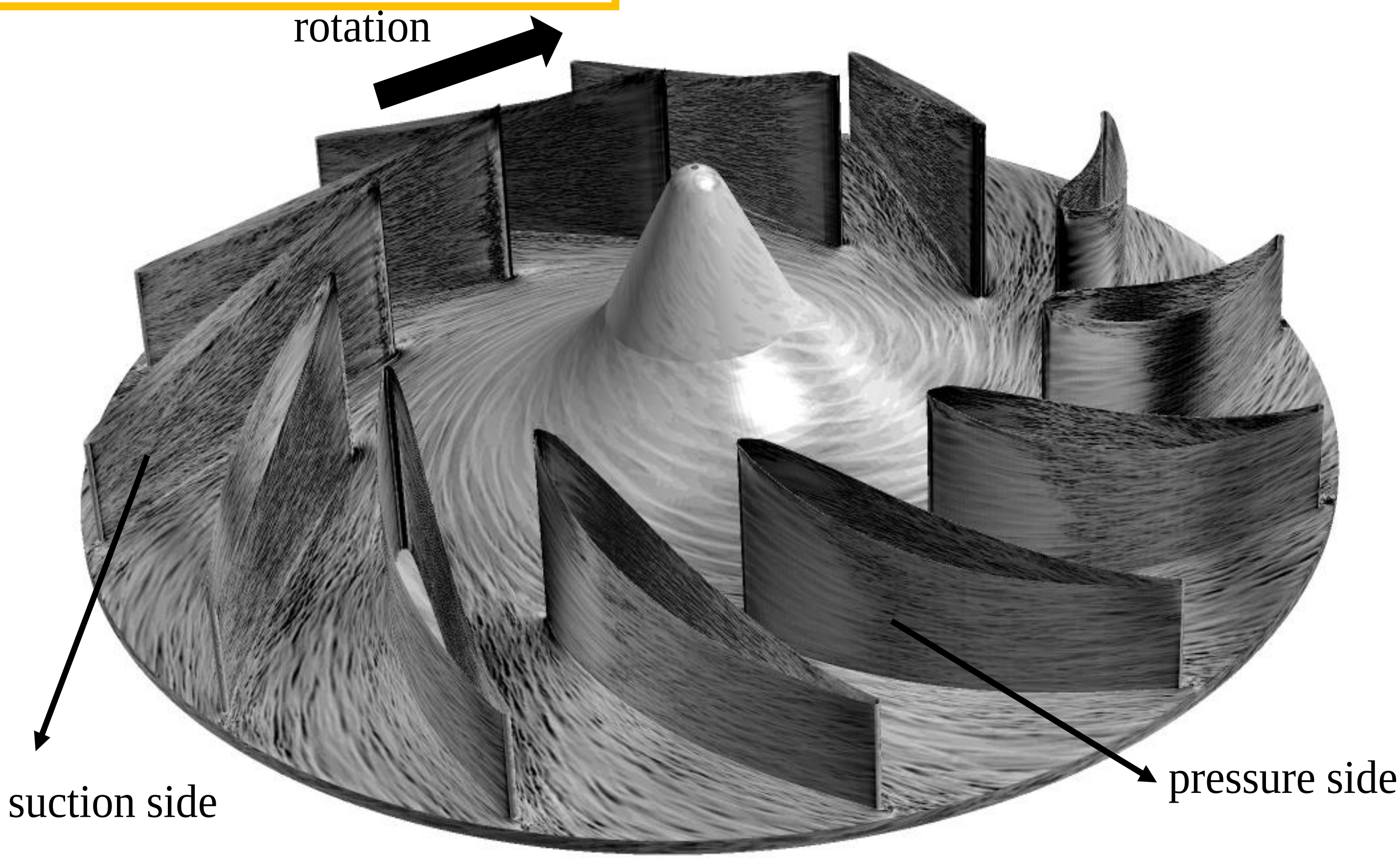
Aeroacoustics Noise from a Blower

- Tonal Noise
  - ✓ Stator-Rotor Interaction
- Broad Band Noise
  - ✓ Flow Separations and/or Secondary flow
  - ✓ Vortex Motions in TBL



Vortex Scale in TBL on Impeller

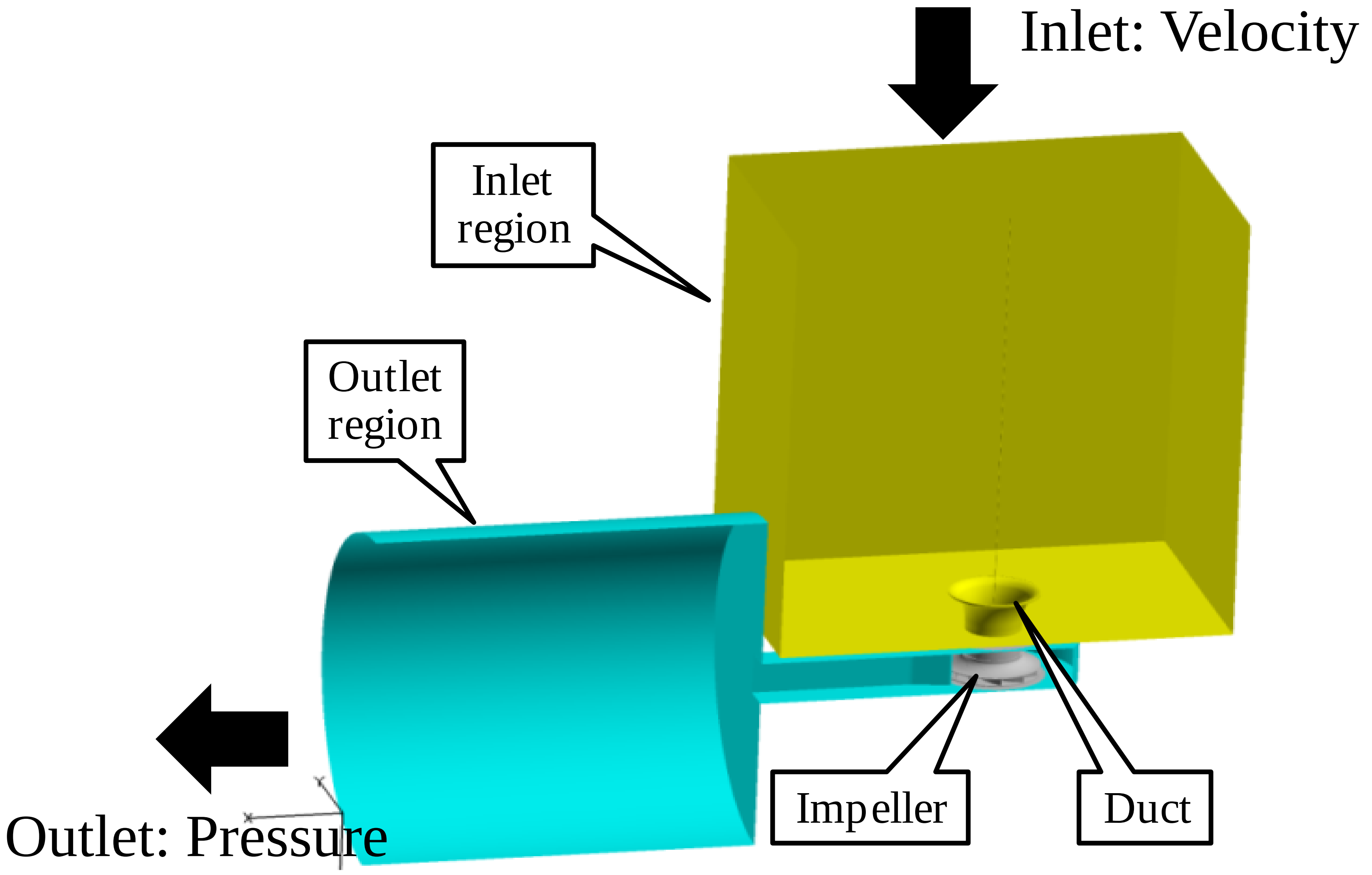
Frictional Velocity: 3.0 m/s
Diameter: 0.15 mm
Spacing: 0.75 mm



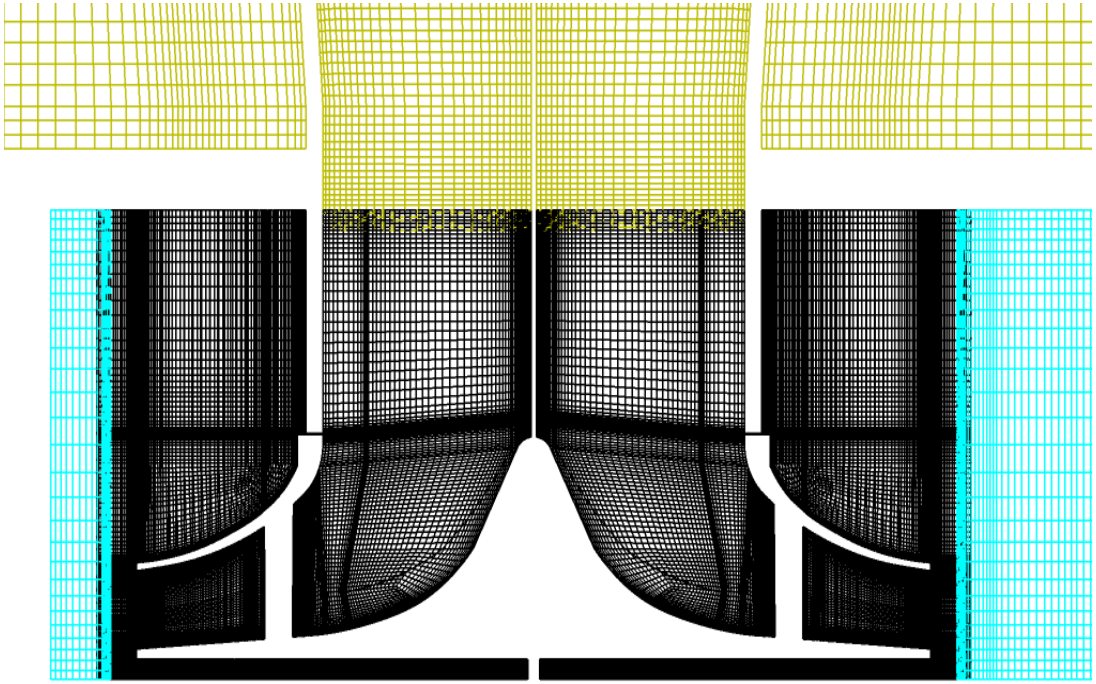
5 billion LES

CONDITIONS

Computational Model



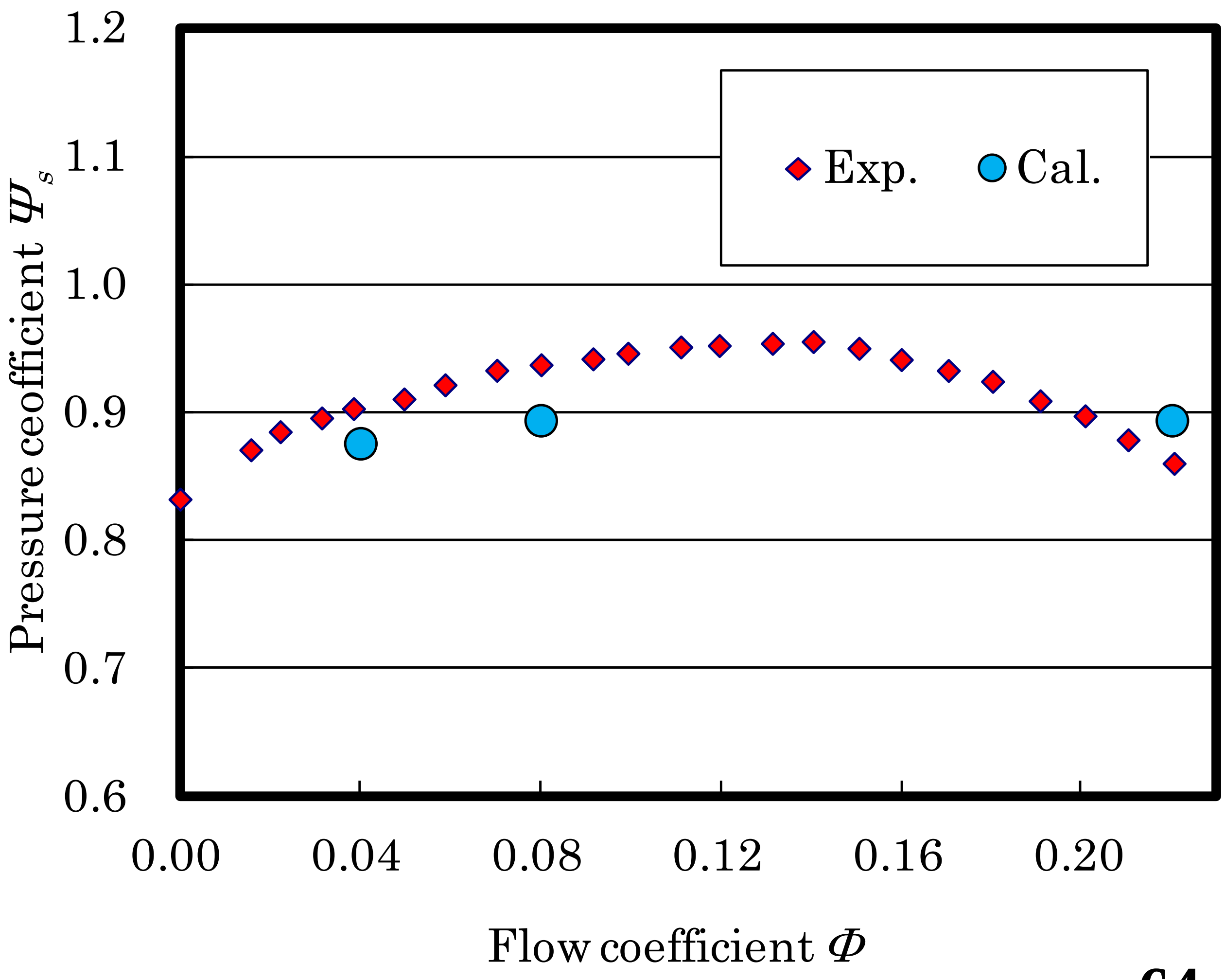
Computational Grids and Cases



- 10 million LES ($\Delta^+ = 80$), 20 revolutions of impeller
- 80 million LES ($\Delta^+ = 40$), 10 revolutions of impeller
- 640 million LES ($\Delta^+ = 20$), 10 revolutions of impeller
- 5 billion LES ($\Delta^+ = 10$), 0.05 revolutions of impeller

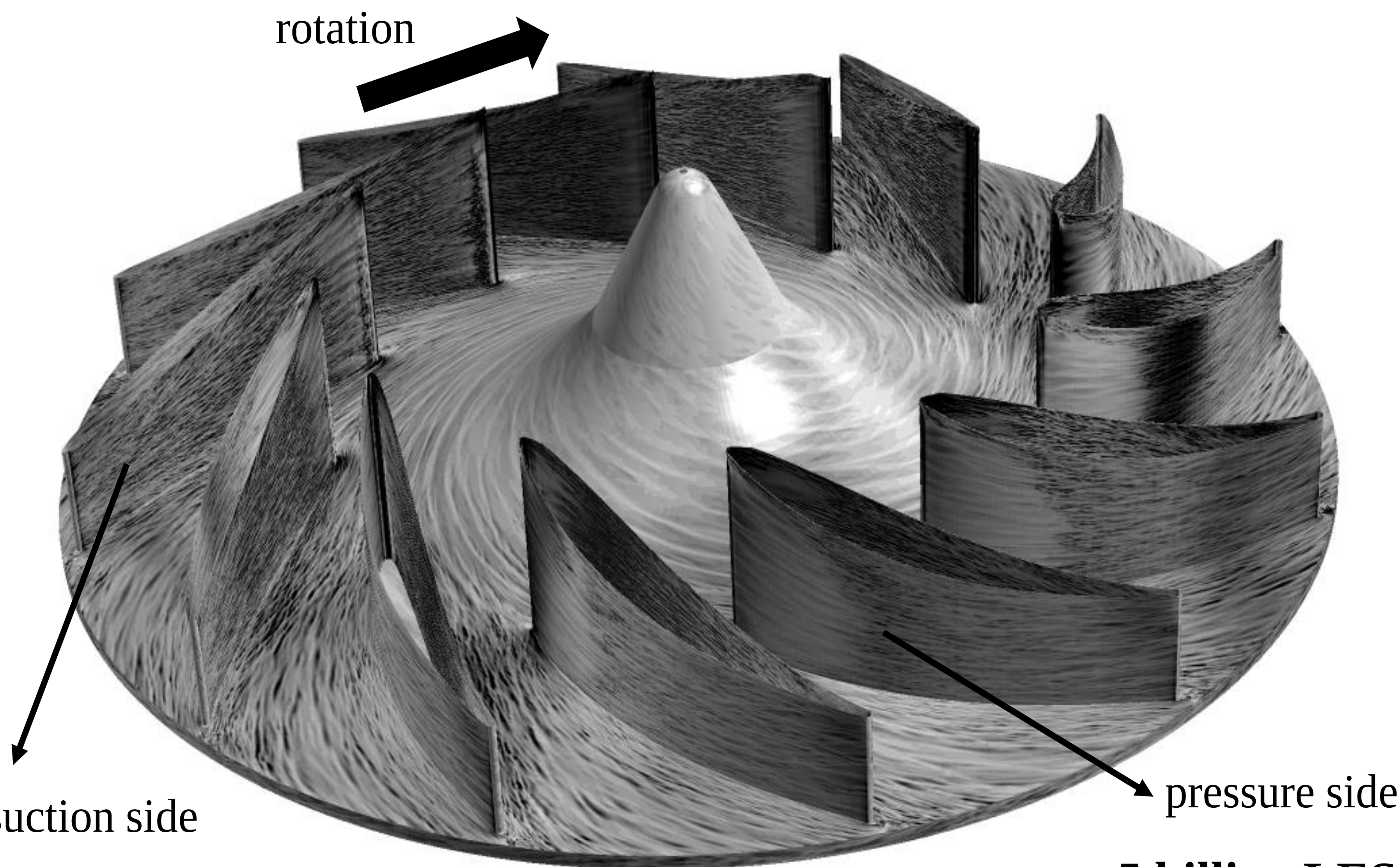
RESULTS

Static Head



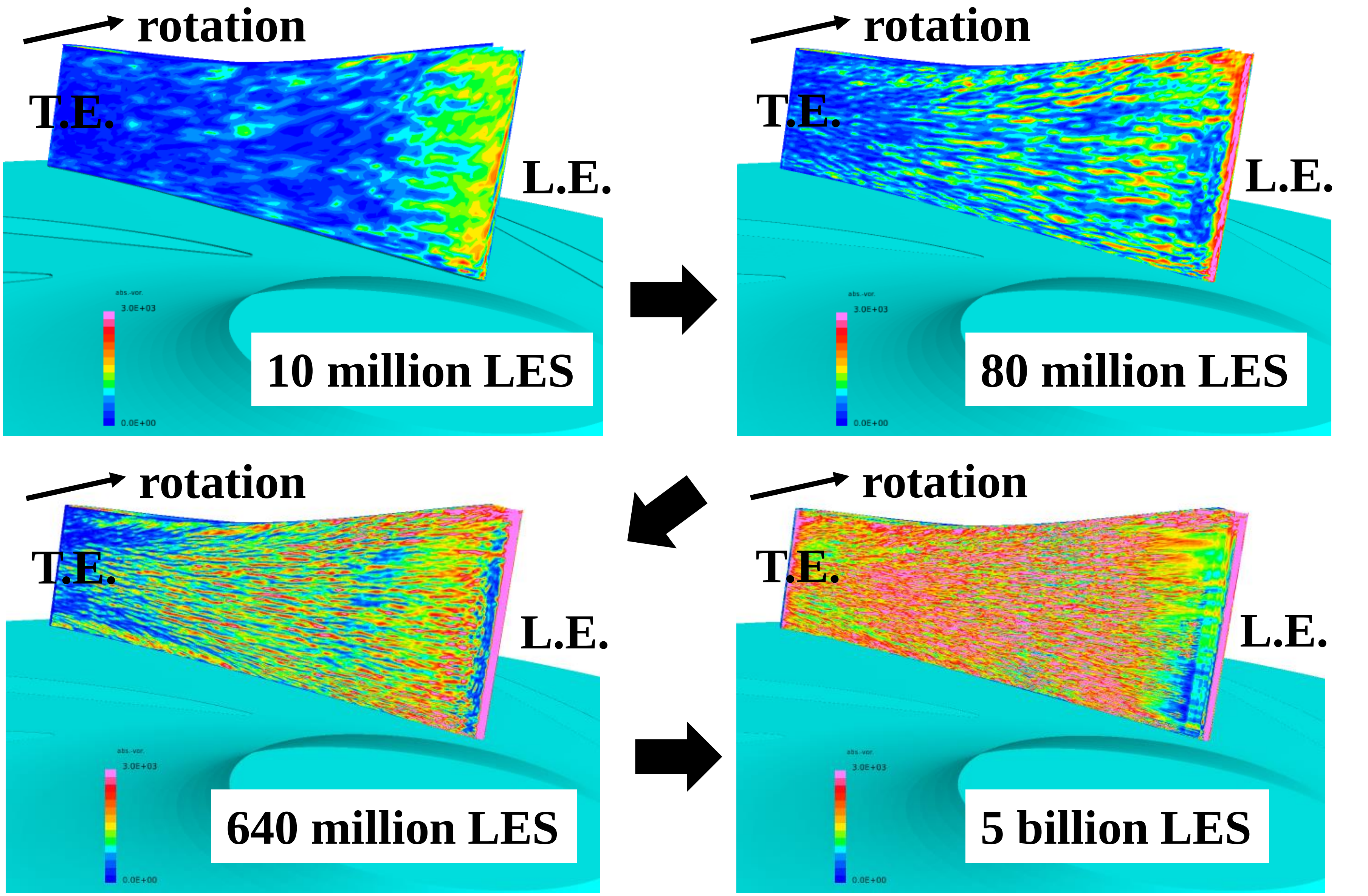
64 million LES

Vortices in TBL on Impeller

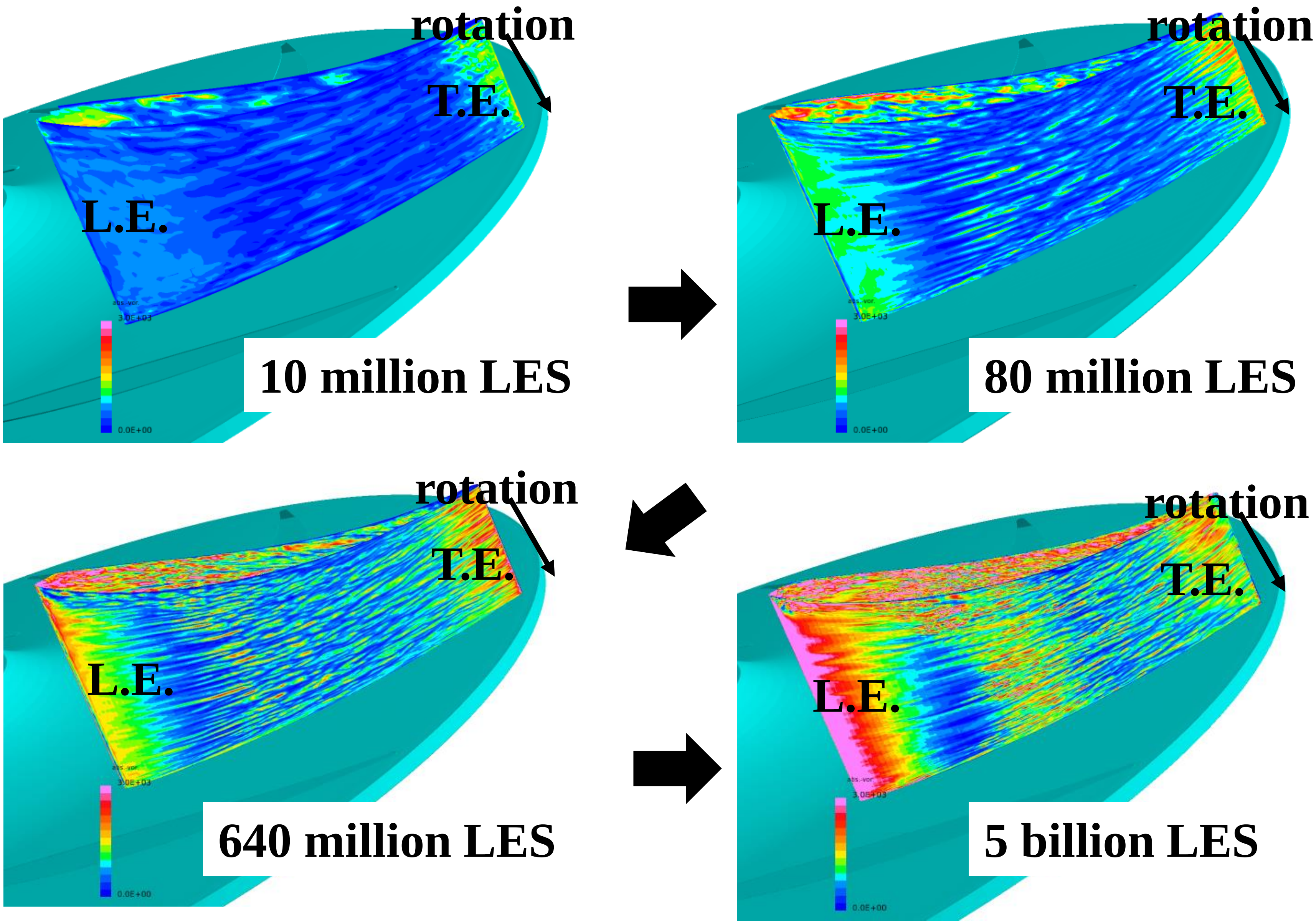


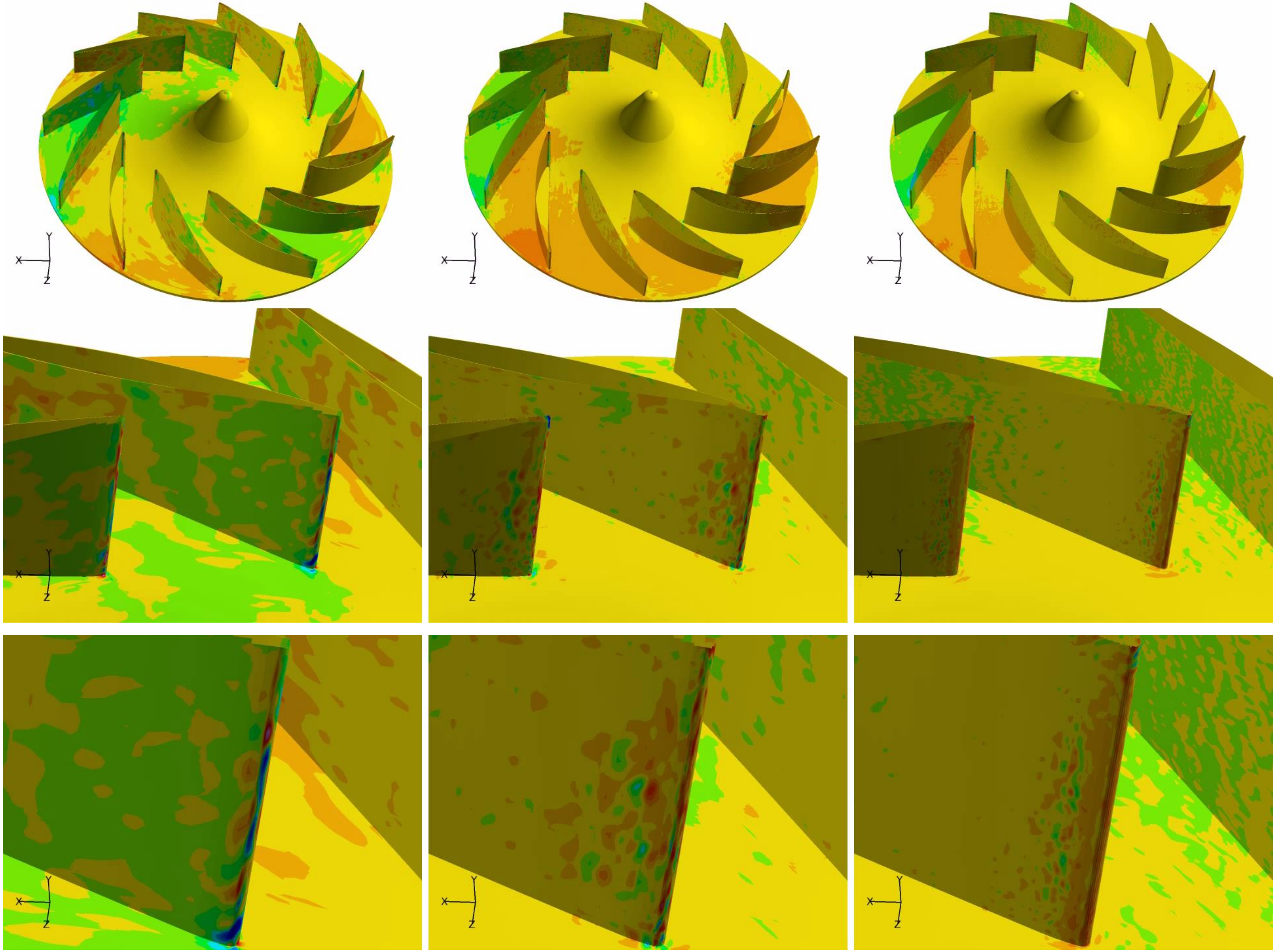
5 billion LES

Vortices in TBL on Suction Side



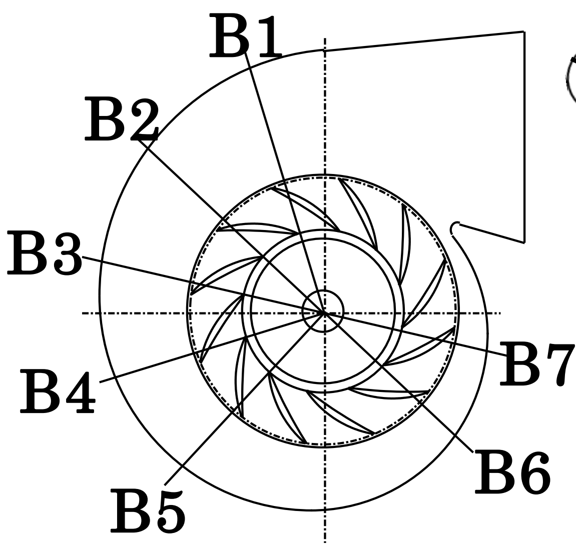
Vortices in TBL on Pressure Side

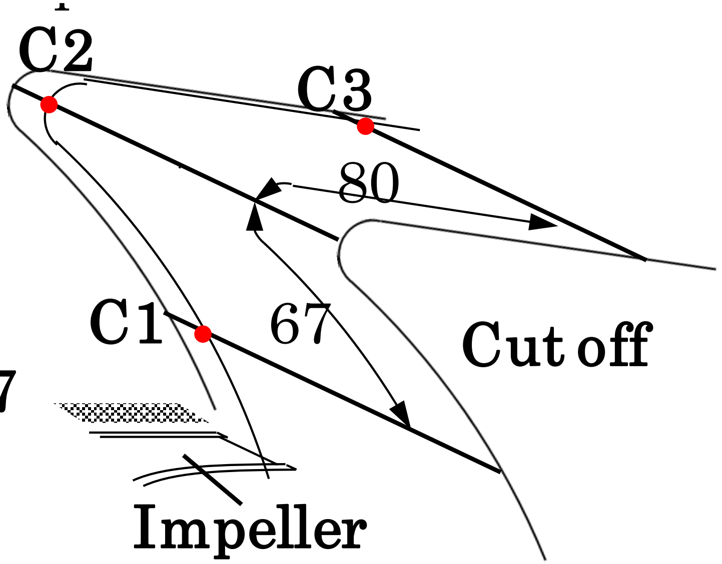


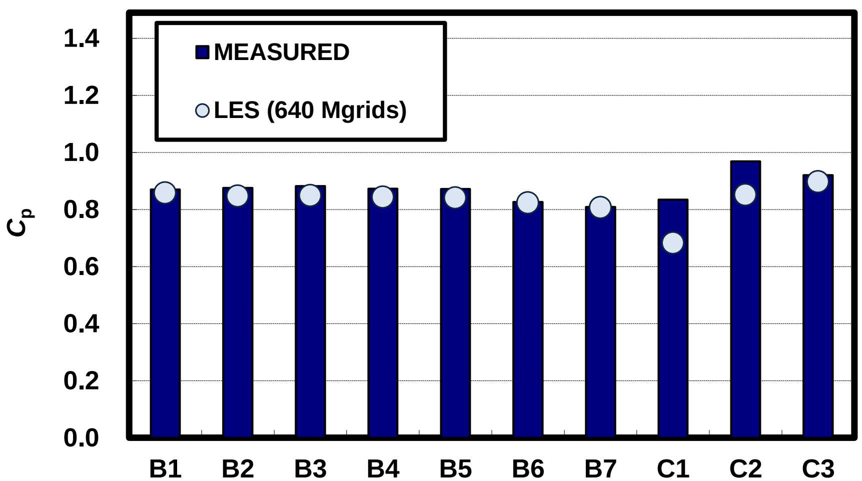


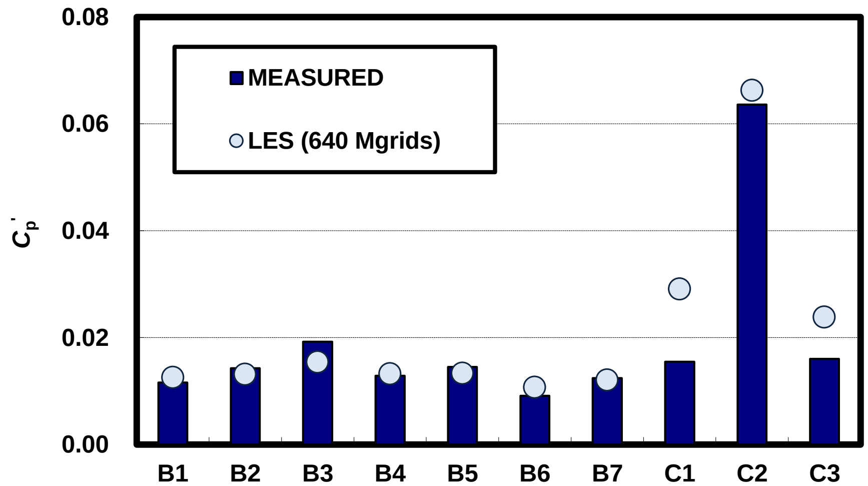
10 million LES **80 million LES** **640 million LES**

Pressure Coefficients



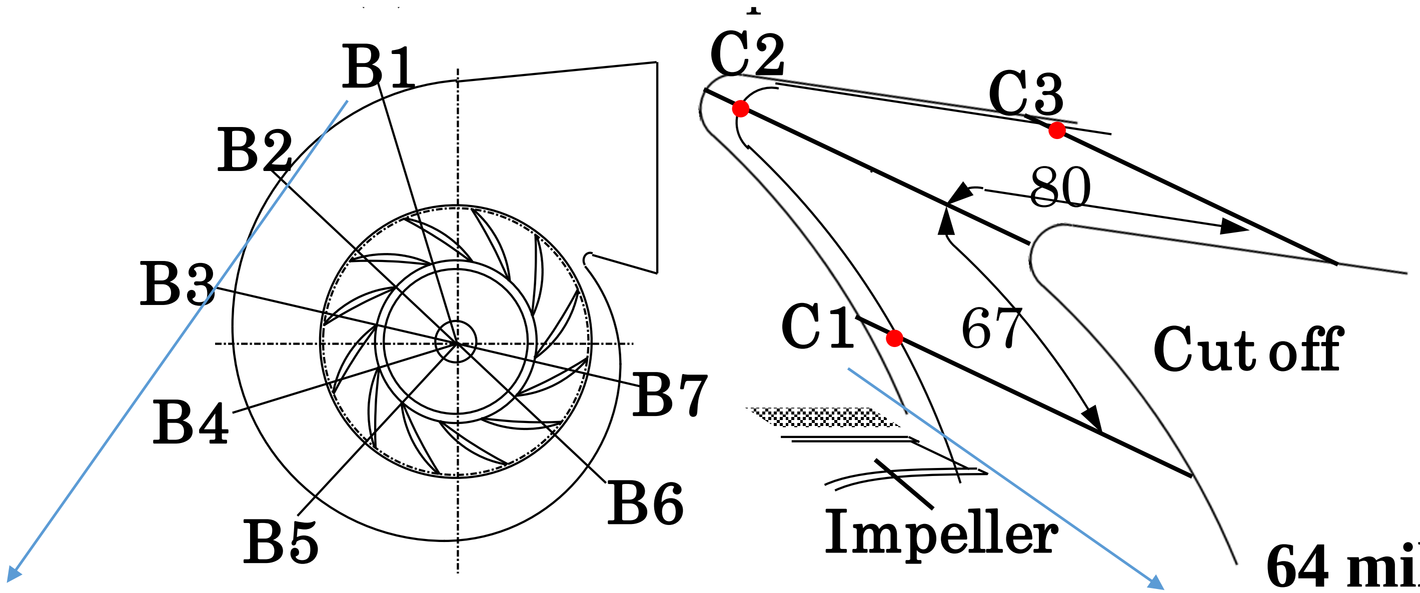




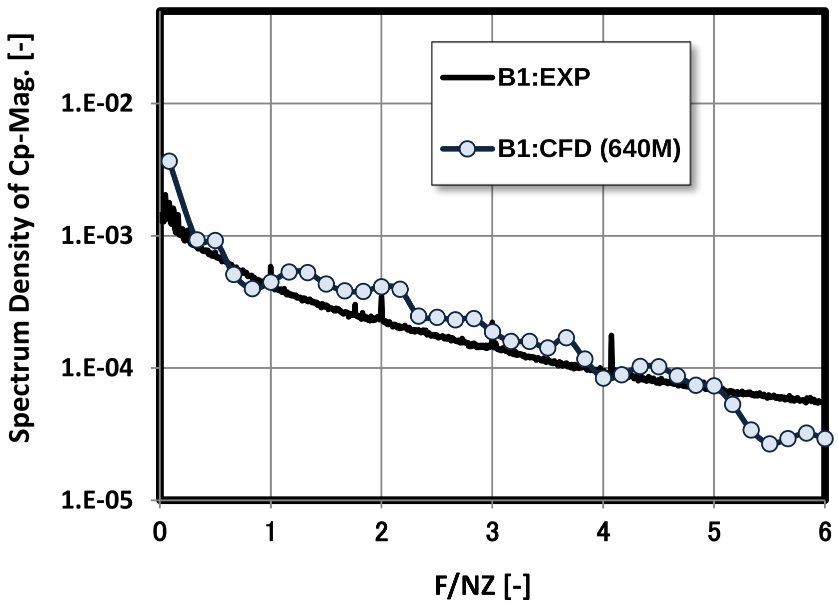


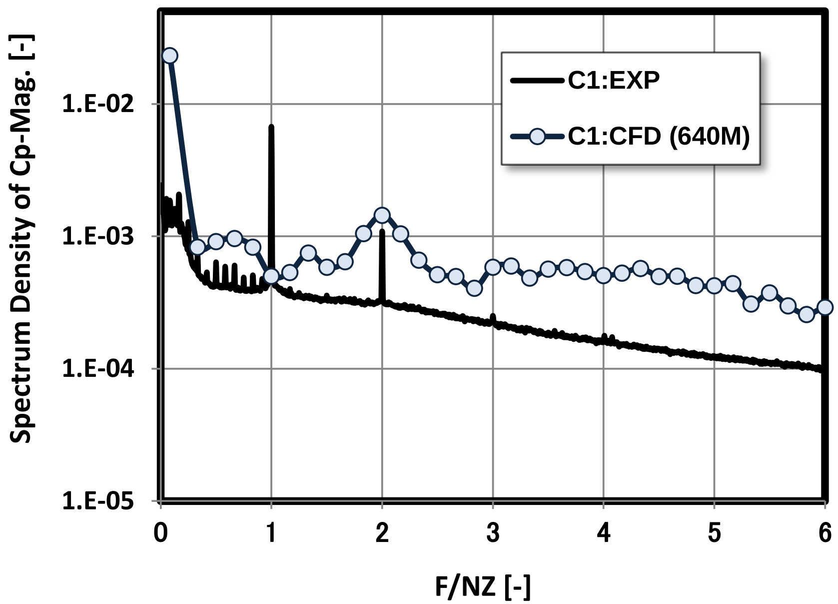
64 million LES

Power Spectra of Pressure Coefficients



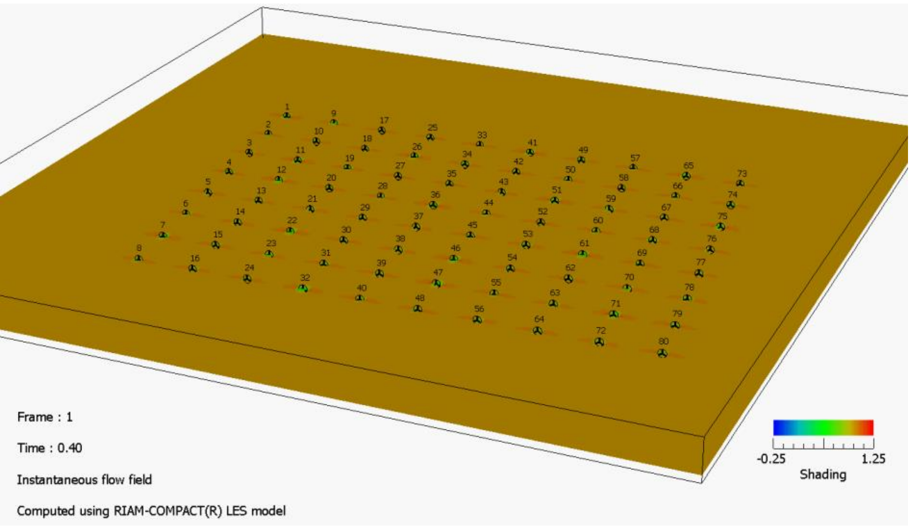
64 million LES

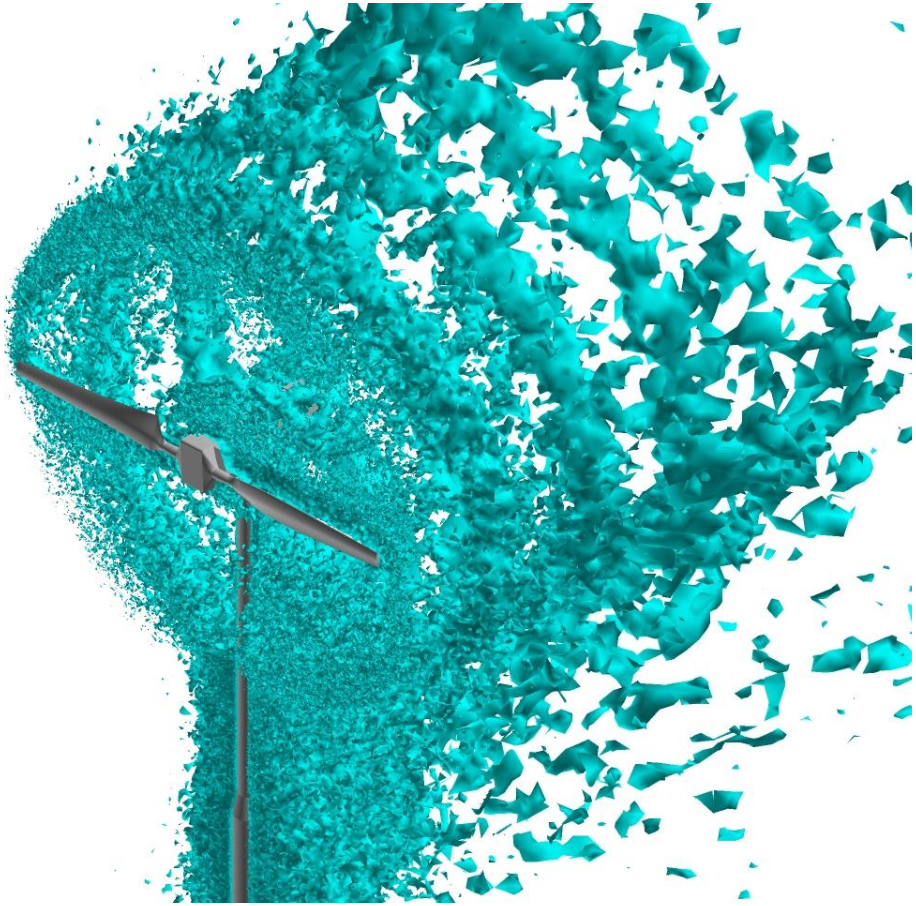




2.4 準直接計算の工学応用4
風車後流の高解像度計算

風車後流の高解像度計算





ウインドファームの流れ解析
（九州大学、提供）

風車まわり流れ解析

3. ポスト京にむけて

重点課題8Cにおける開発項目とその目的

- FFBの高速化（コデザイン）、理化学研究所
  ソフト・ハードあわせ100倍の高速化
- 圧縮性コードの開発
  空力騒音の直接計算、オーバーセット計算のロバスト性向上
- LBMベースの流体解析システムFFXの開発、九州大学
  完全自動メッシュ作成、1兆規模大規模計算
- 乱流モデルの開発
  準直接計算の抜本的計算コストの削減

LBMコードによる乱流の準直接計算

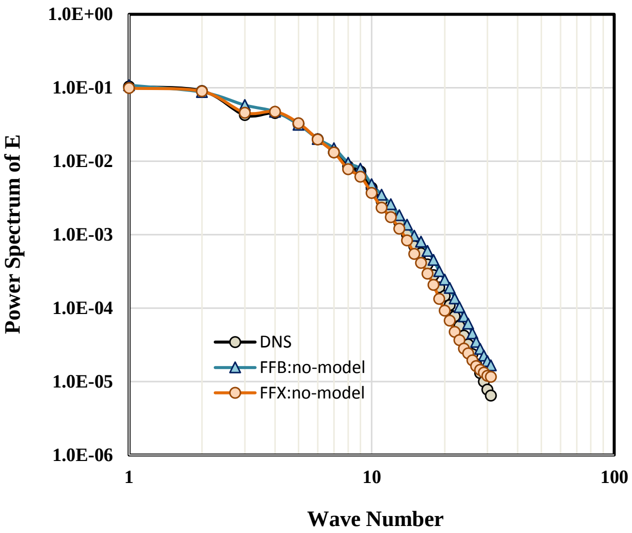
$$f_i\left(t+\Delta t, x_\alpha + c_{i,\alpha}\Delta t\right) = f_i(t, x_\alpha) - \frac{1}{\tau}\left[f_i(t, x_\alpha) - f_i^{eq}(t, x_\alpha)\right]$$

対流項　　拡散項

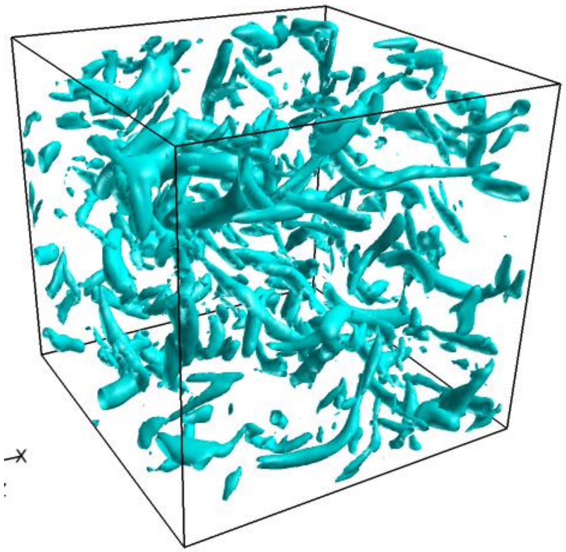
対流項は隣接グリッドからのコピーから計算され精度が高い

LBMコードによるNACA0012翼まわり流れ解析
（九州大学）

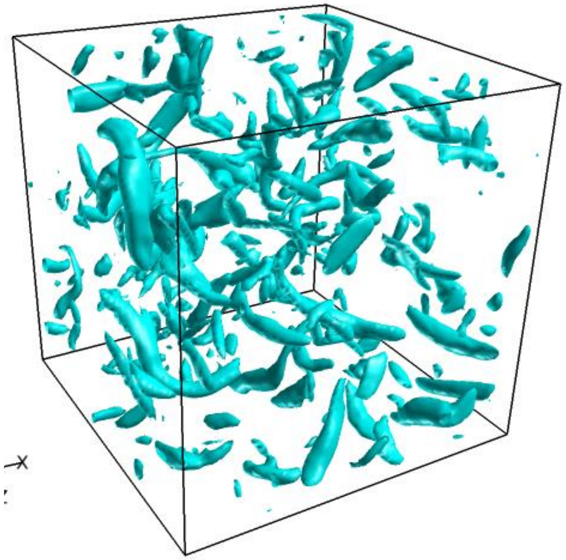
精度検証-1：一様等方性乱流



乱流エネルギースペクトル



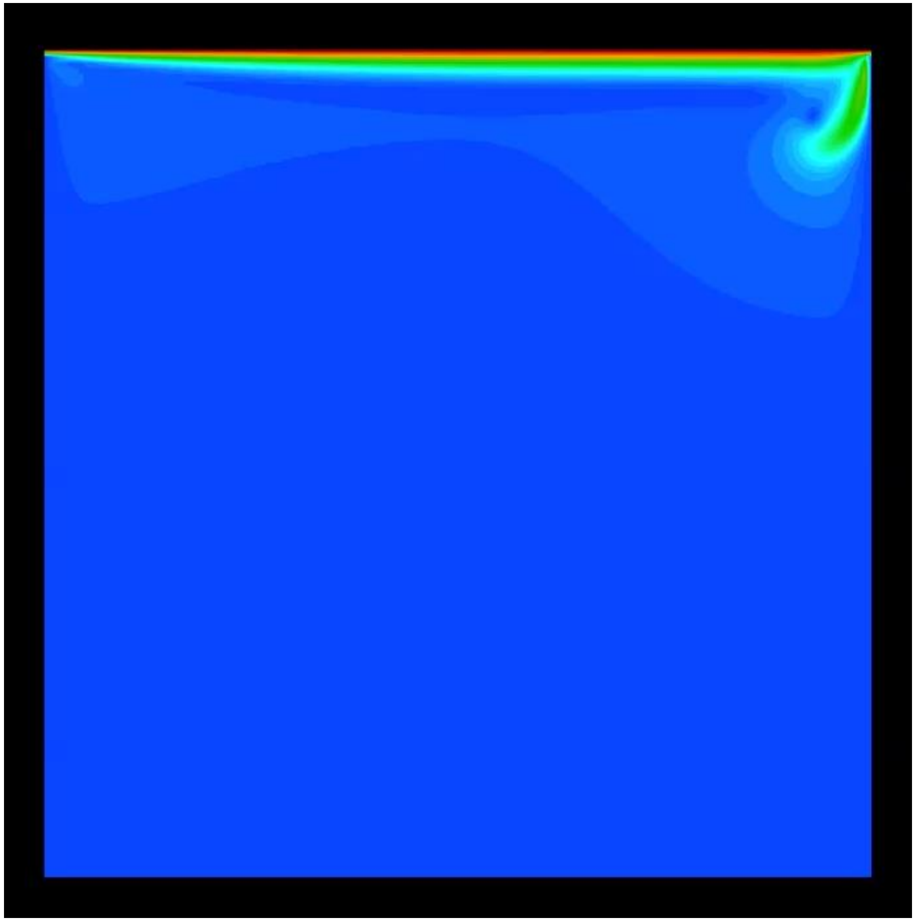
FFB:Re=121

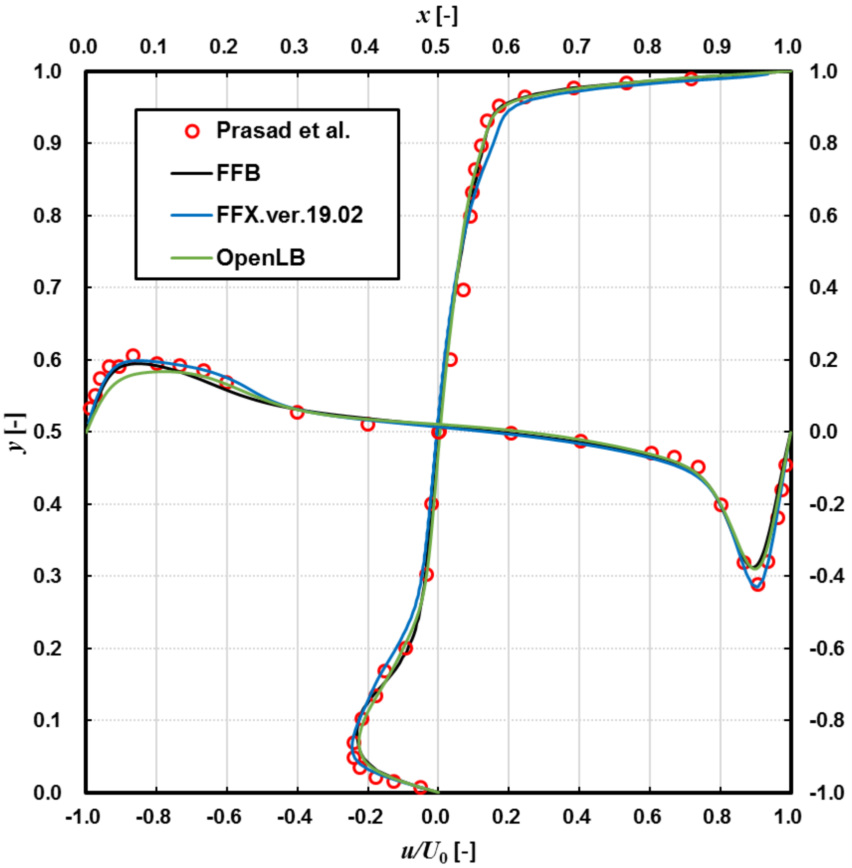


FFX:Re=121

乱流構造の可視化結果

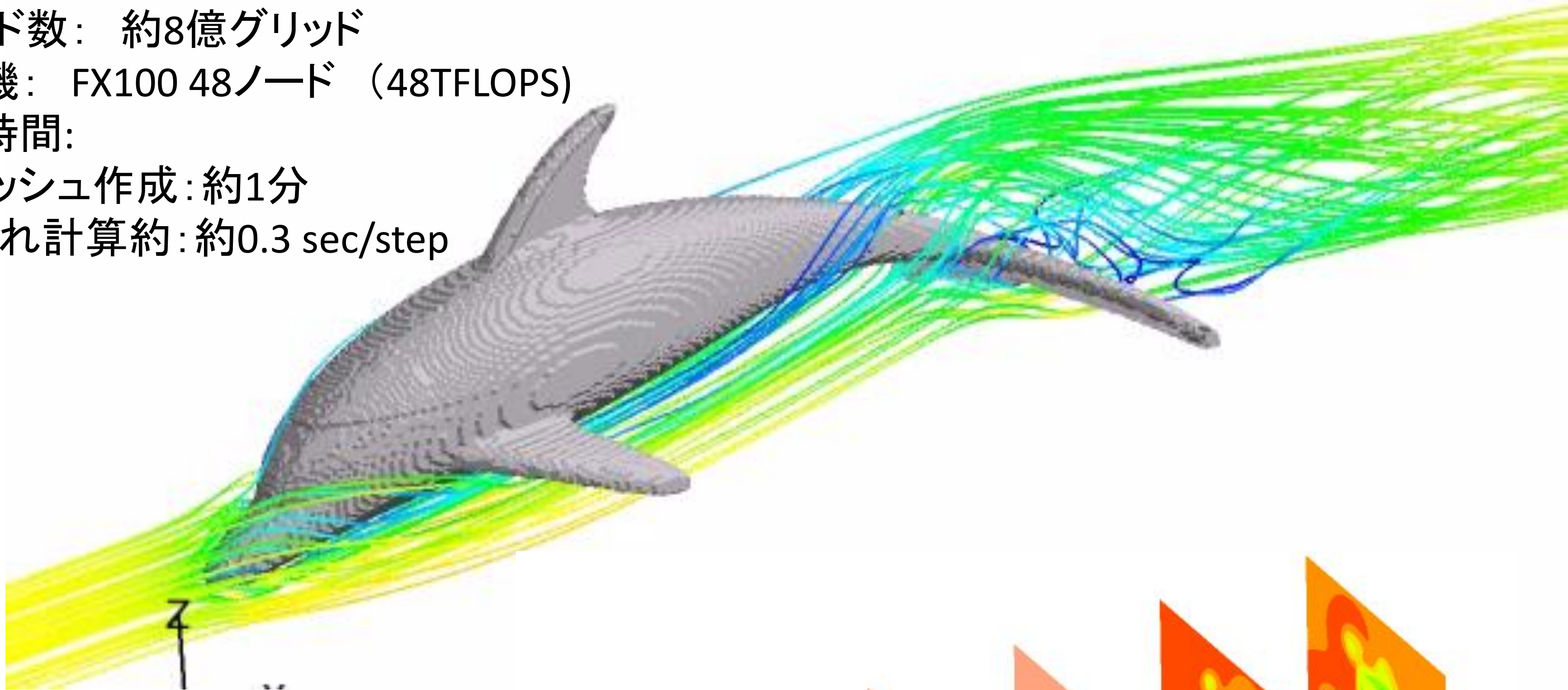
精度検証-2：Cavity流れ



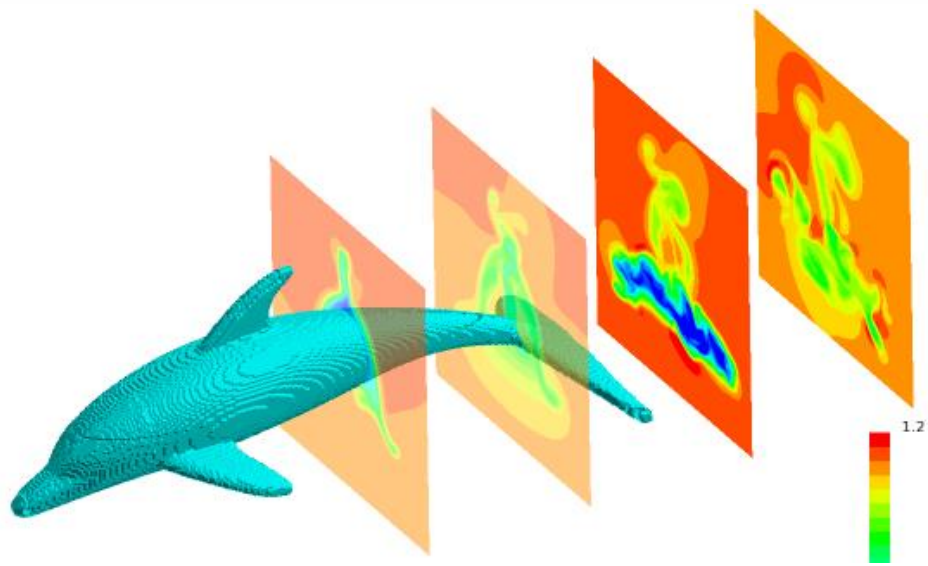


精度検証-3：複雑形状まわり流れ

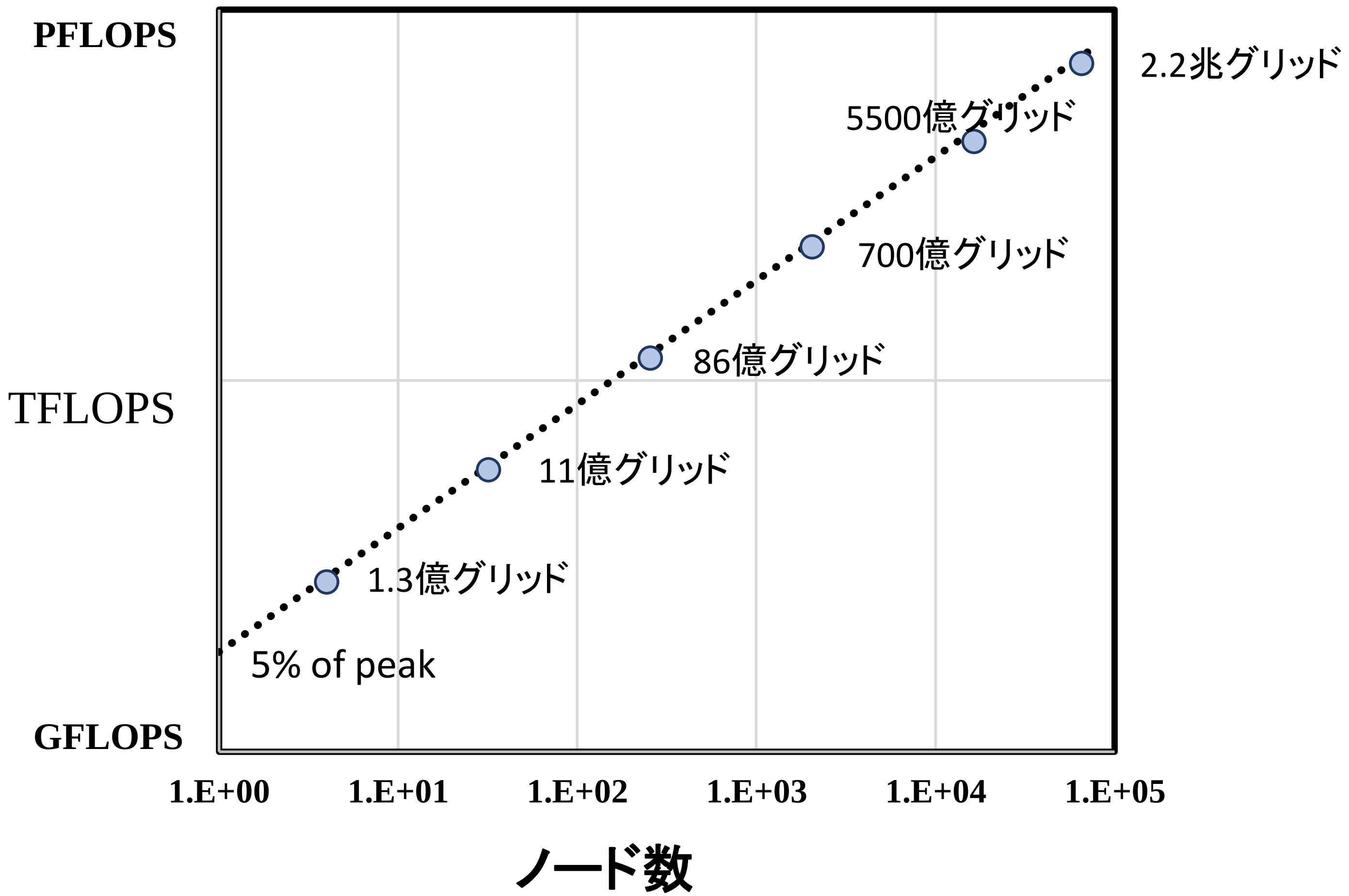
- ■ グリッド数：　約8億グリッド
- ■ 計算機：　FX100 48ノード　（48TFLOPS)
- ■ 処理時間:
  - ✓ メッシュ作成：約1分
  - ✓ 流れ計算約：約0.3 sec/step



- ■ グリッド数：　約500億グリッド
- ■ 計算機：
  - ✓ 京 1,536ノード　（192 TFLOPS)
- ■ 処理時間:
  - ✓ メッシュ作成：1分
  - ✓ 流れ計算約：約1.1 sec/step



京におけるweak-scaleベンチマーク結果



京のほぼフルノードを用いて2.2兆グリッドまでスケールすることを確認

おわりに

おわりに

年代	2000年代	2010年代	2020年代
計算機性能	GFLOPS級	PFLOPS級	EFLOPS級
代表的な計算機	ES	京	ポスト京
計算規模	Million 10^6	Billion 10^9	Trillion 10^{12}

製品性能予測と現象理解