Toward acceleration of industrial applications of fluid-flow simulation empowered by HPC

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CISS
Center for Research on
Innovative Simulation Software

Outline

- **Industrial Applications**
- **Flow Solvers**
- **Applications Examples**
- **Consortium Projects to Promote Industrial Applications (to be presented in site)**
- **Conclusions and Perspectives**

Industrial Applications

Industrial Applications of Wall-resolving Simulations

Wall-resolving Simulations can be applied to:

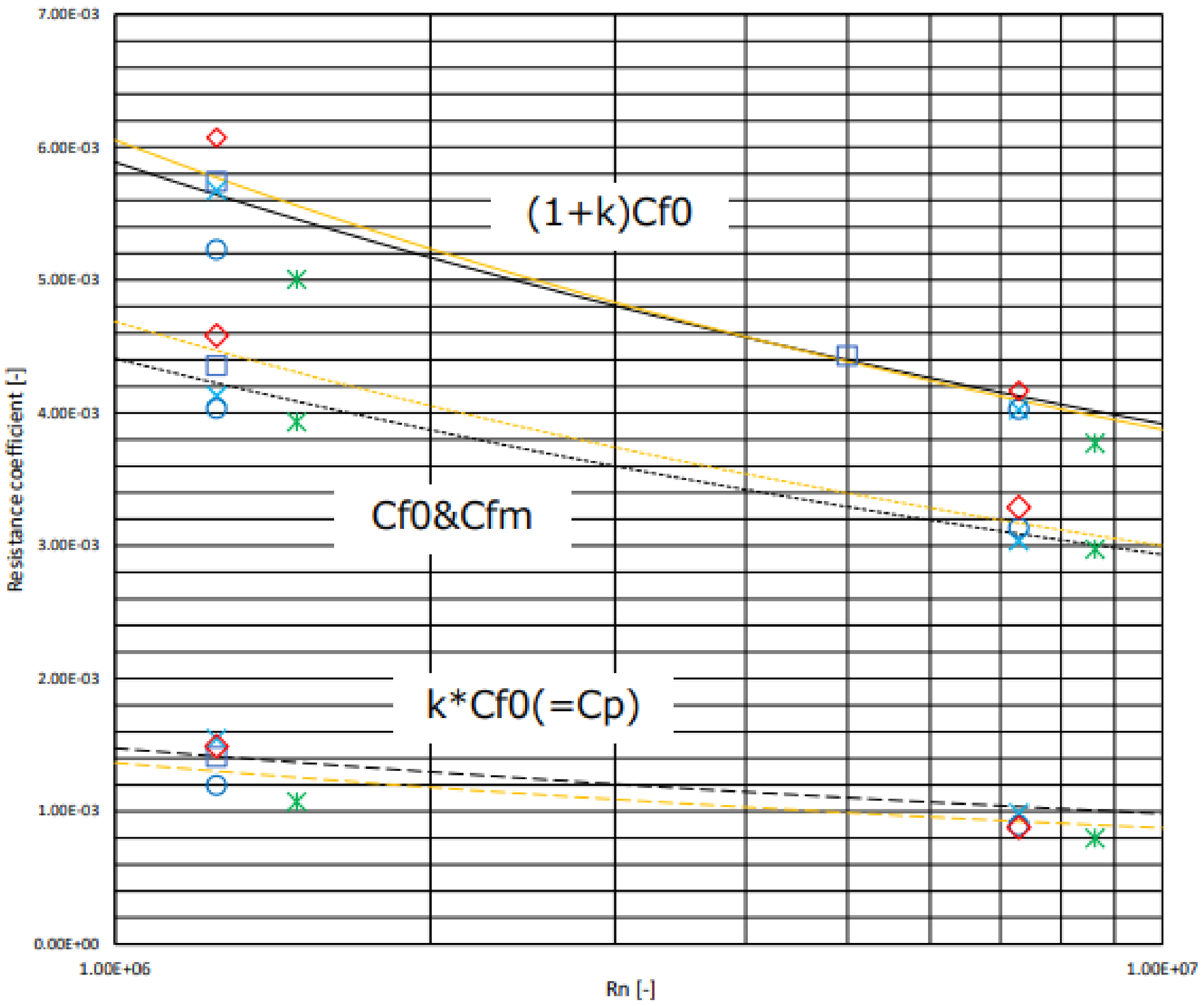
- Predict performance of a product for completely replacing tests
- Identify the essential phenomena that dominate product performance
- Understand the reason why an unexpected phenomenon occurs
- Generate accurate data sets to be referenced for developing prediction model

Replacing Tests

400 m long, 18 m wide, 8 m deep
water tank with a maximum towing speed of 15 m/s

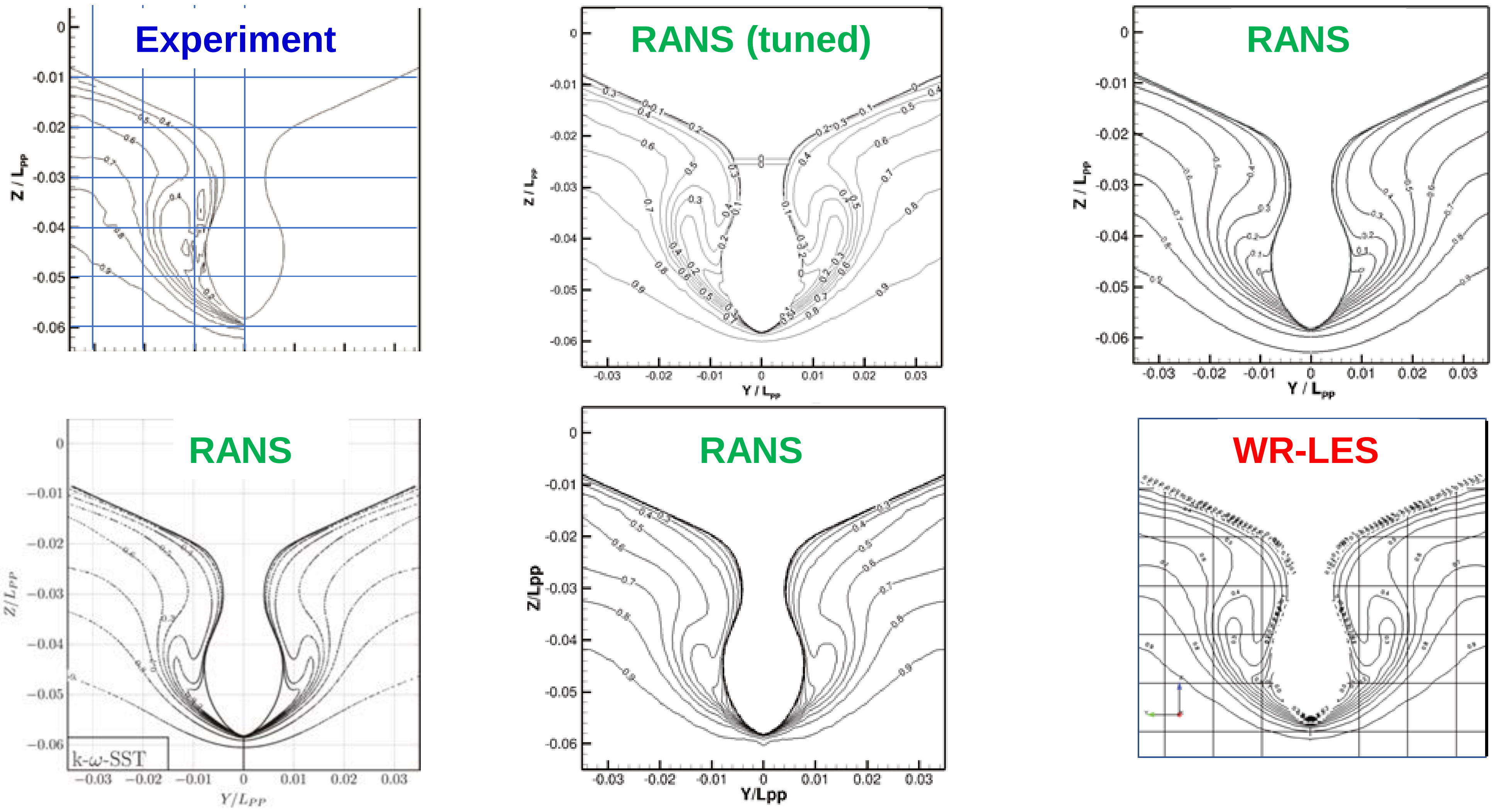
Resistance predicted by RANS Simulations

- Total resistance predicted by RANS quite scatters.



Examples of RANS-based Simulations

- Wake profiles predicted by RANS near Stern

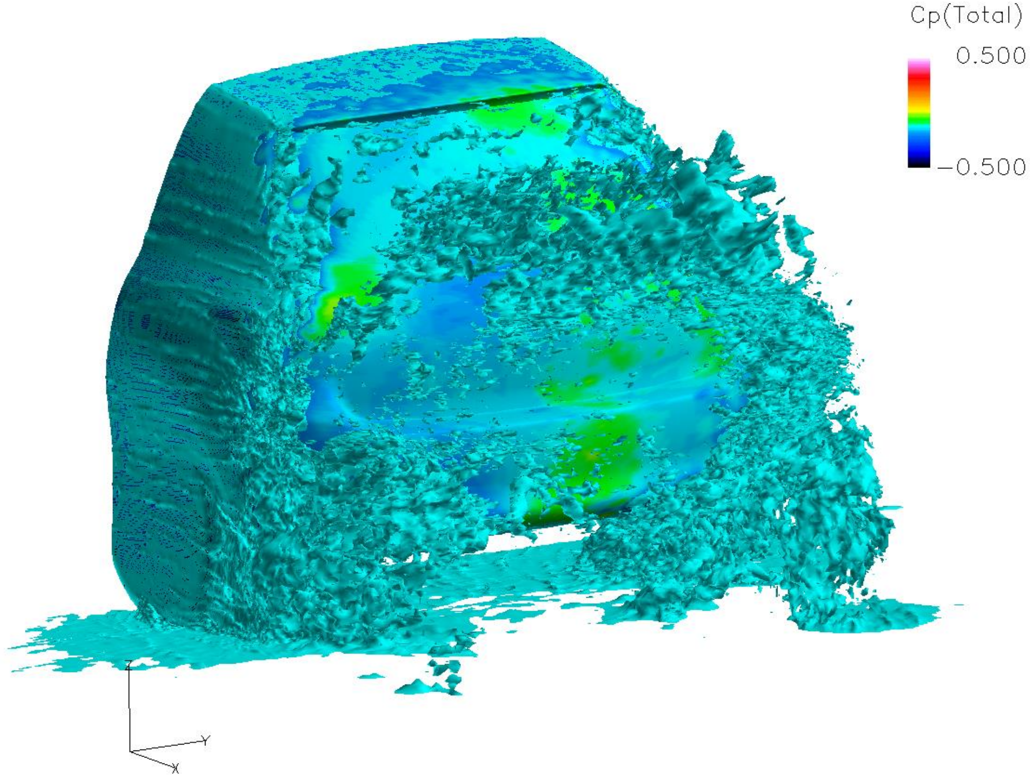


Flow Solvers

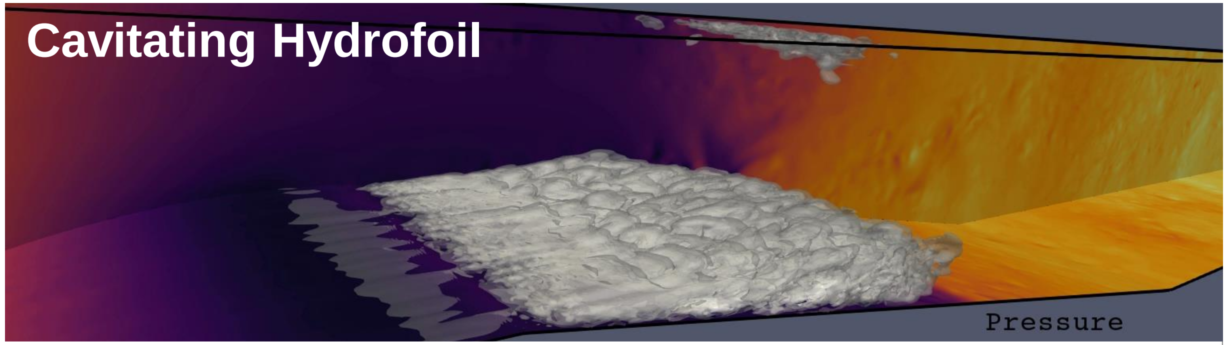
Chisachi KATO, et al., Journal of Applied Mechanics, 2003
Chisachi KATO, et al., Computers & Fluids, 2007

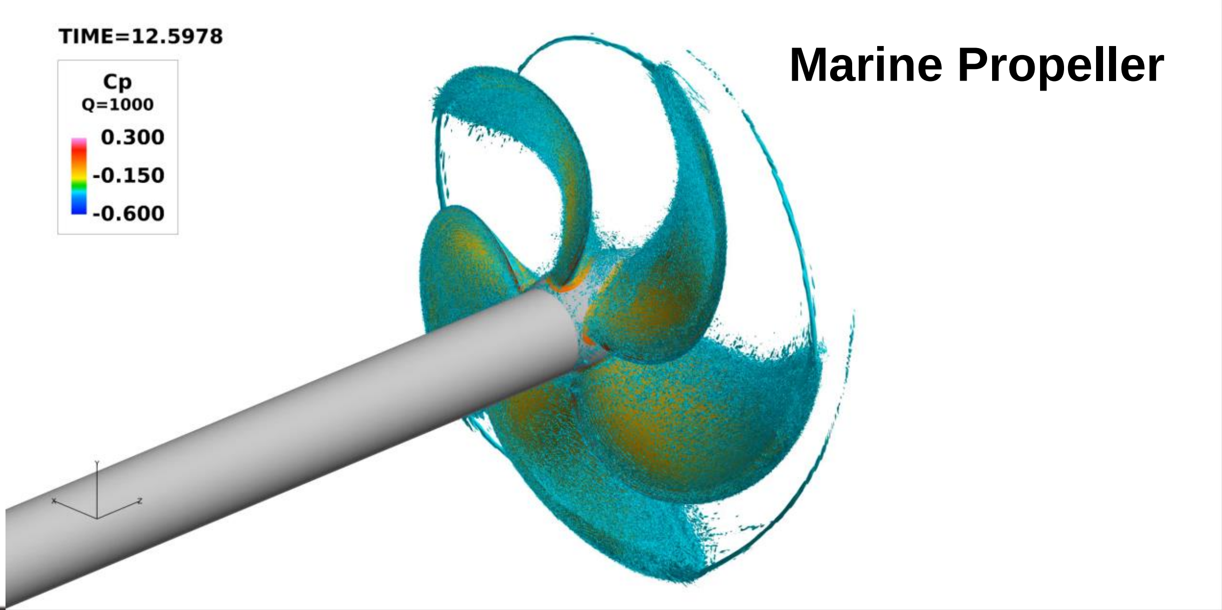
FrontFlow/blue (FFB) Flow Solver

- FEM-based incompressible/compressible Flow Solver
- Developed for Industrial Applications of WR-LES
- Features Automated Mesh Refinement and Overset Method



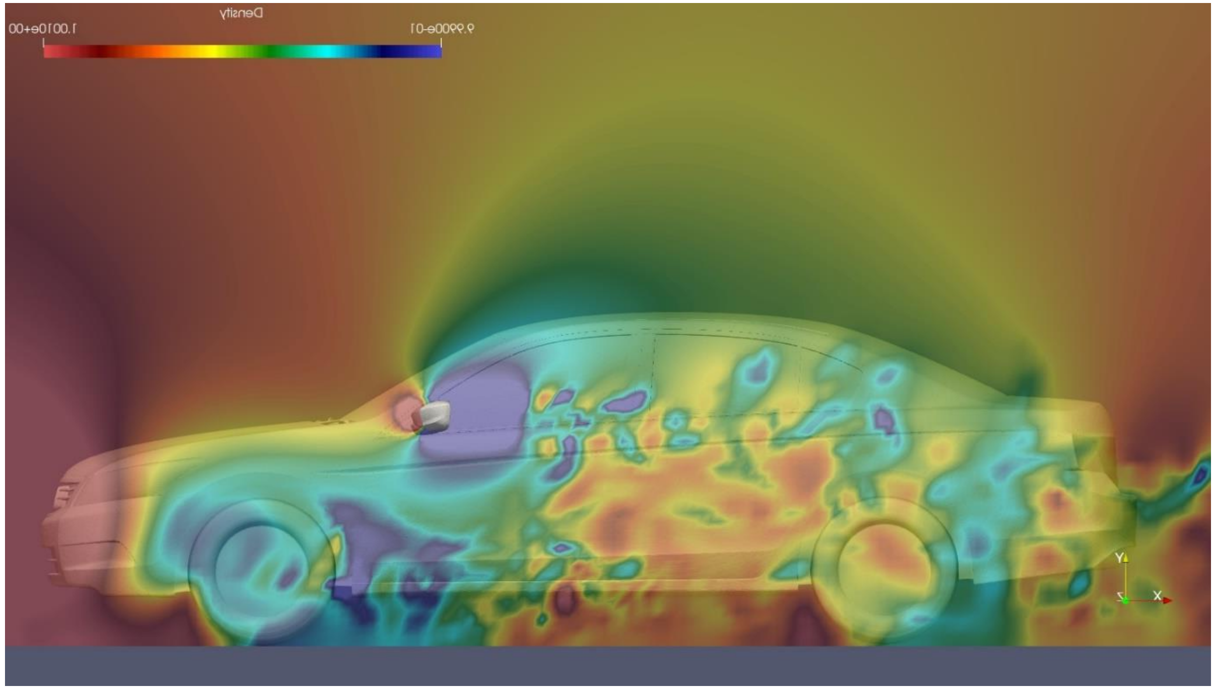
Automobile Wake



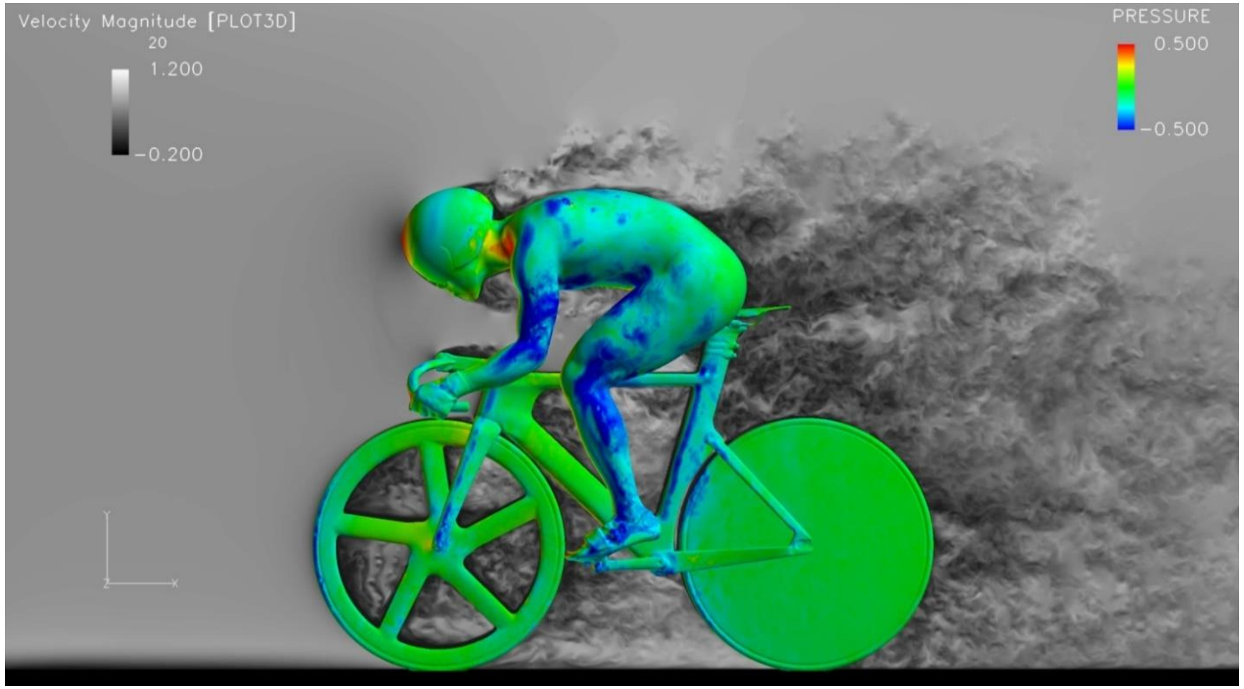


FrontFlow/X (FFX) Flow Solver

- LBM-based compressible Flow Solver
- Developed for Industrial Applications of Direct Sound Simulations
- Features Completely Mesh-free Solver



Automobile Aeroacoustics Simulation



Bicycle-racing Aerodynamic Simulation

Features and Drawbacks of LBM Solver

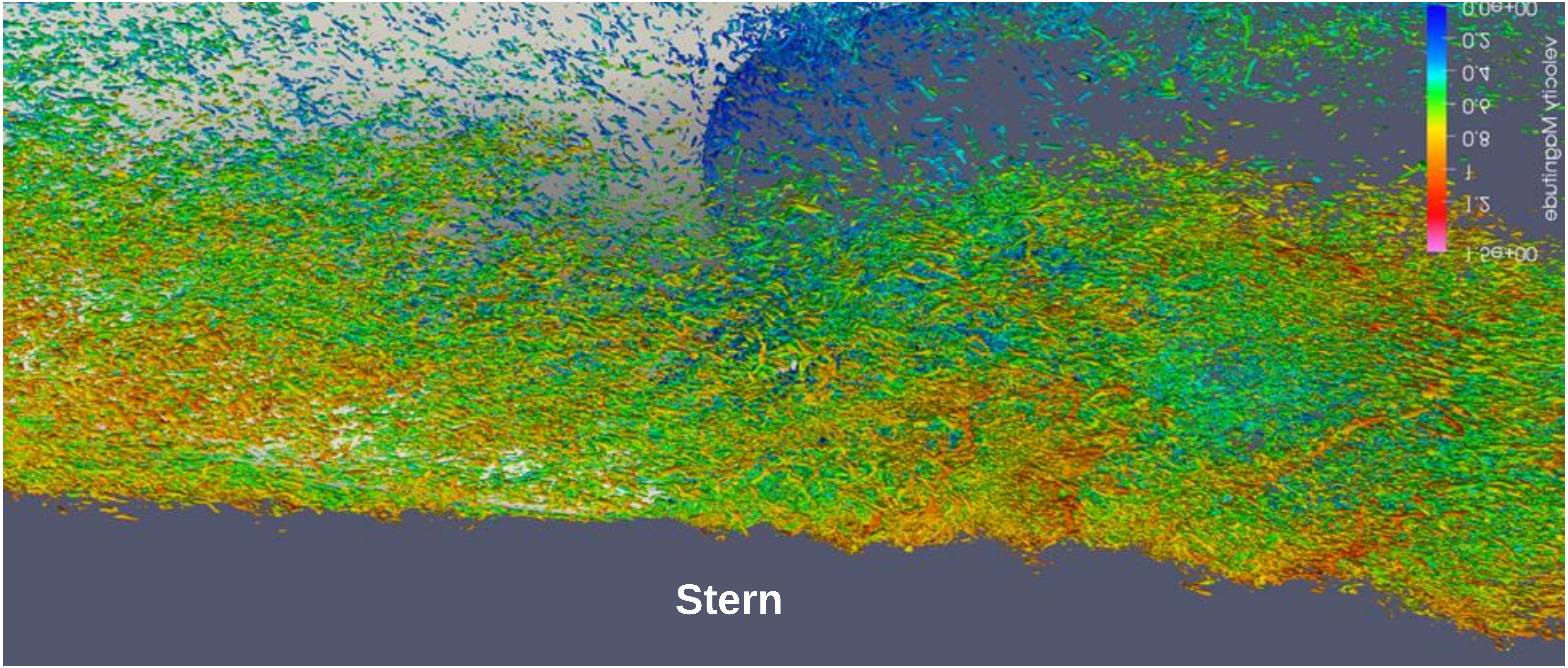
- **Features**
  - **Best suited for fully-automated mesh generation**
  - **Exact solution for convective motion**
  - **Very low memory and computational costs per grid and time step**

- **Drawbacks**
  - **Limited to low-Mach-number flow and is not suited for thermodynamic applications**
  - **Near-wall momentum transfer affected by collision models**
  - **Huge time steps required for developing flow field**
  - **Acoustic waves affected by relaxation time coefficient**

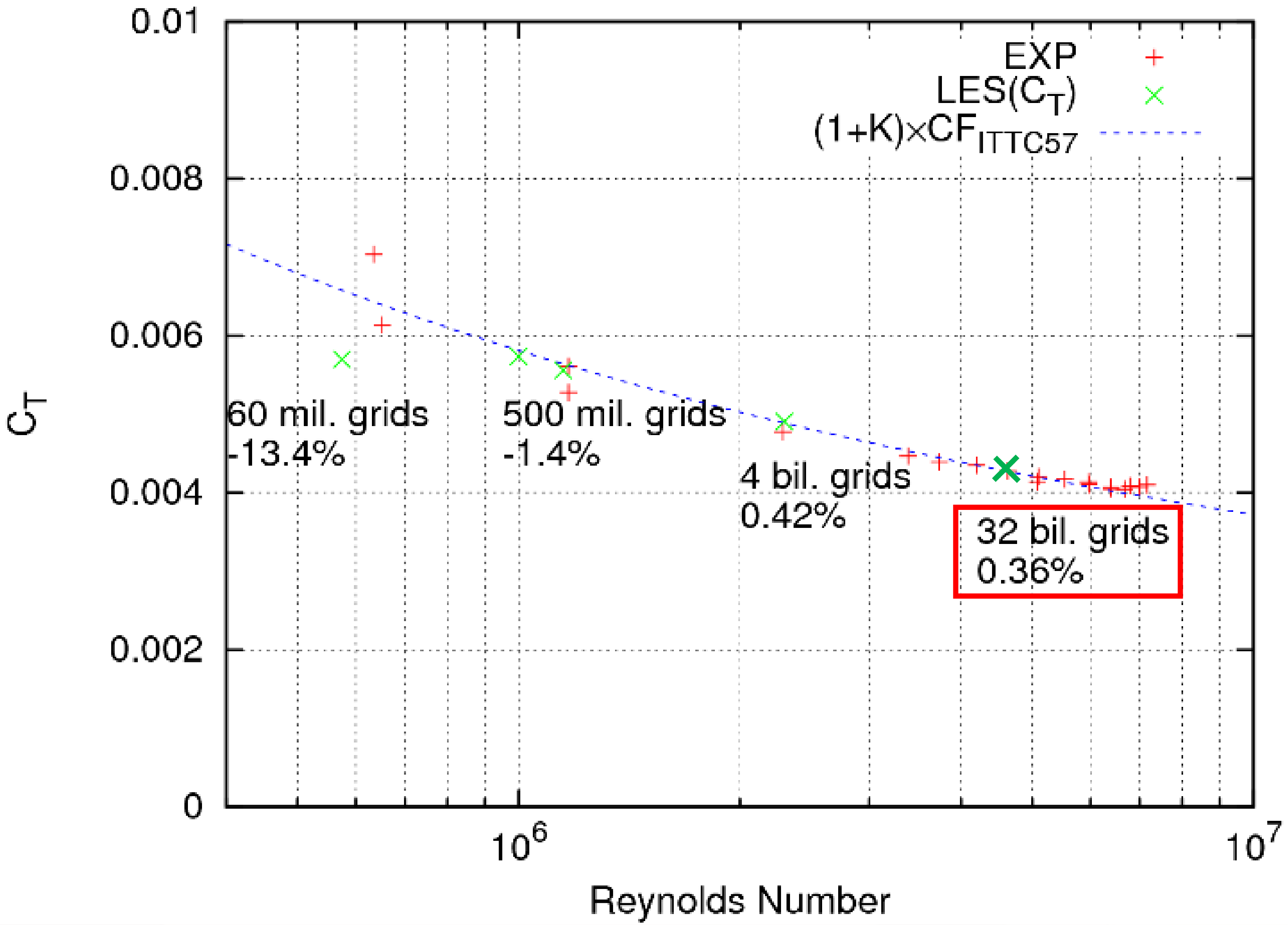
Ship Hydrodynamics Applications

Resistance Test for KVLCC2 Vessel

- Turbulent eddies computed by WR-LES near Stern

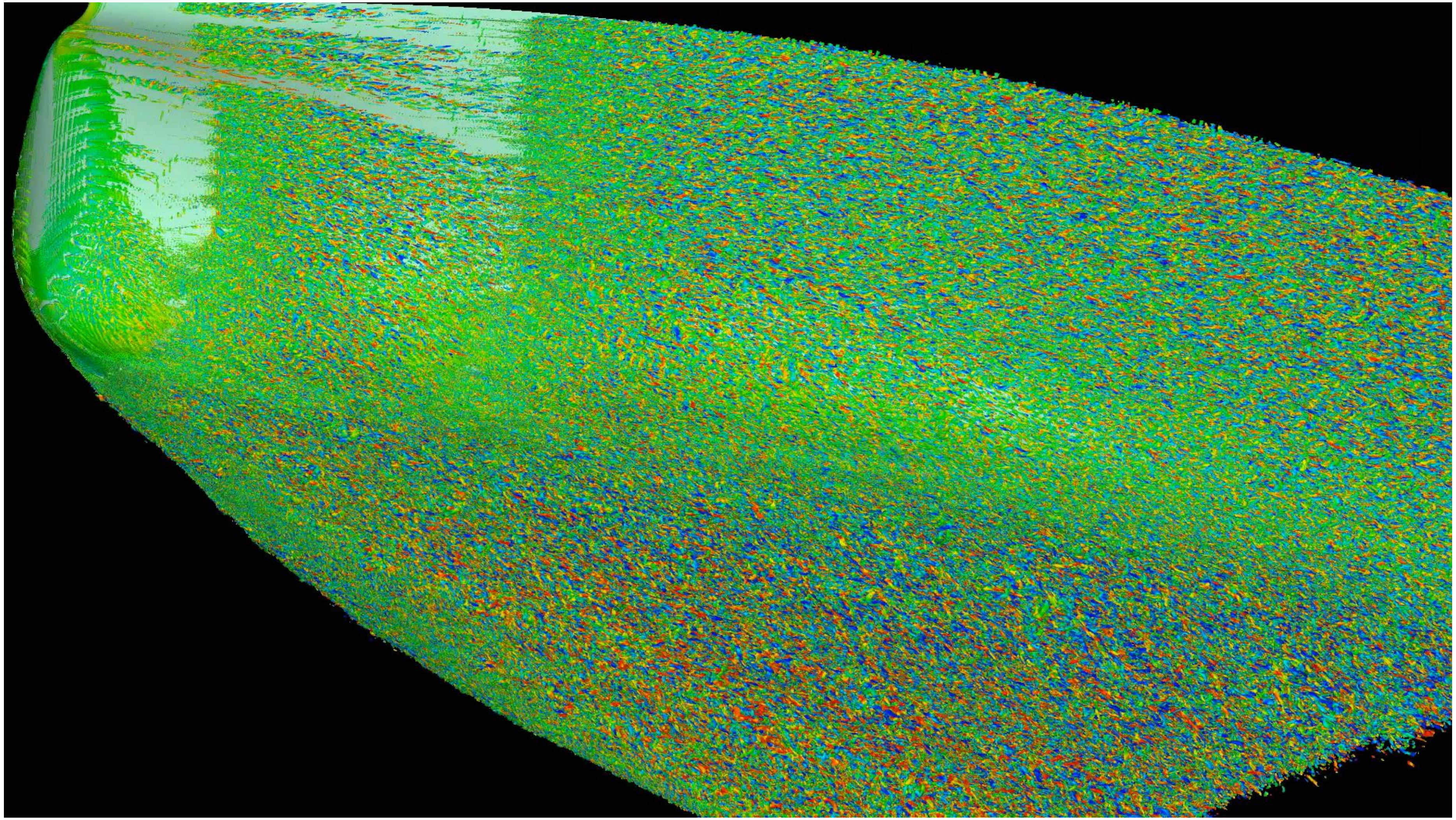


Predicted Total Resistance of KVLCC2



Wall-Resolved LES for Another Vessel

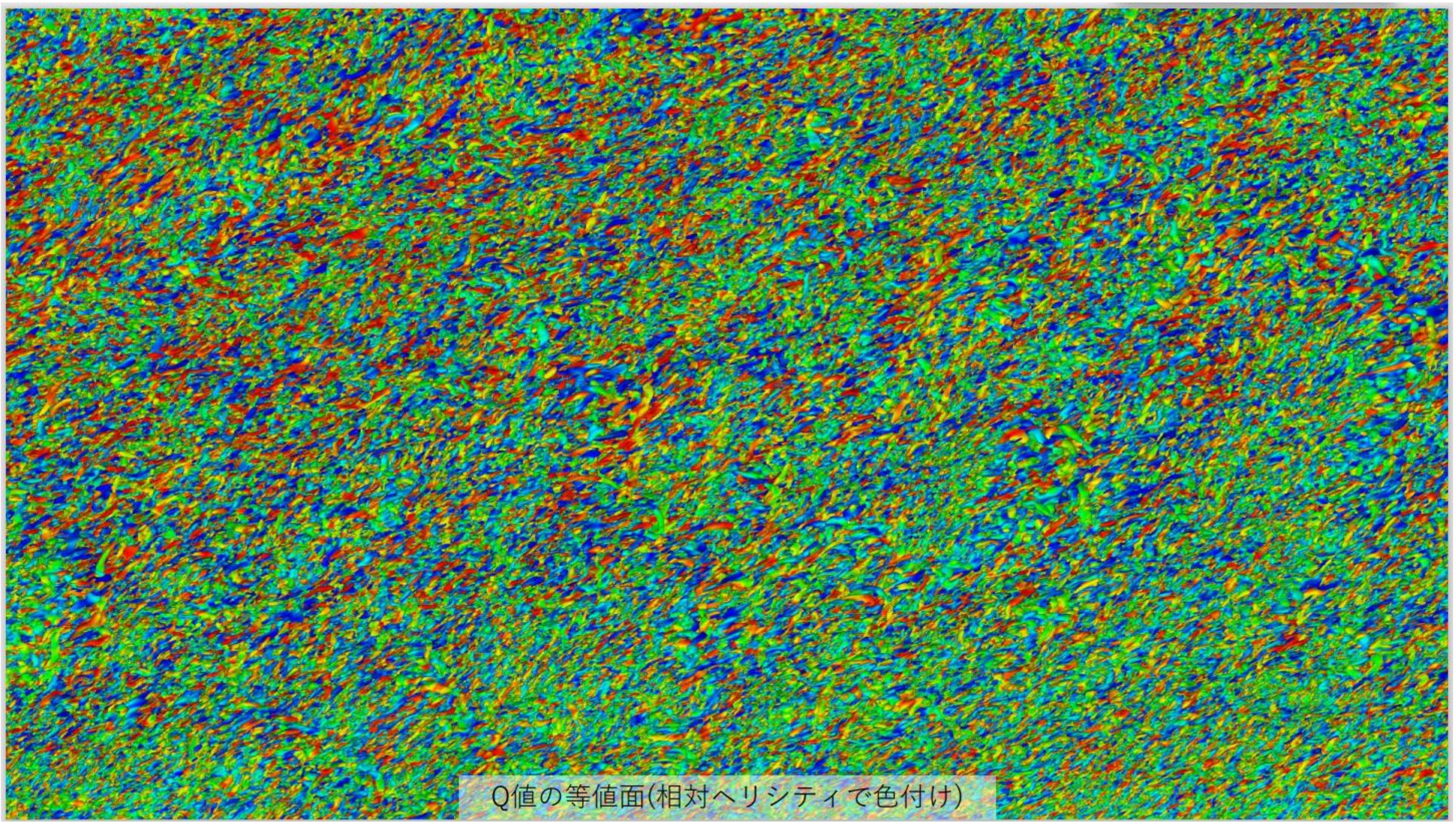
- 68 billion-element Finite Element Computation



Courtesy of Shipbuilding Research Centre of Japan

Wall-Resolved LES for Another Vessel (cont'd)

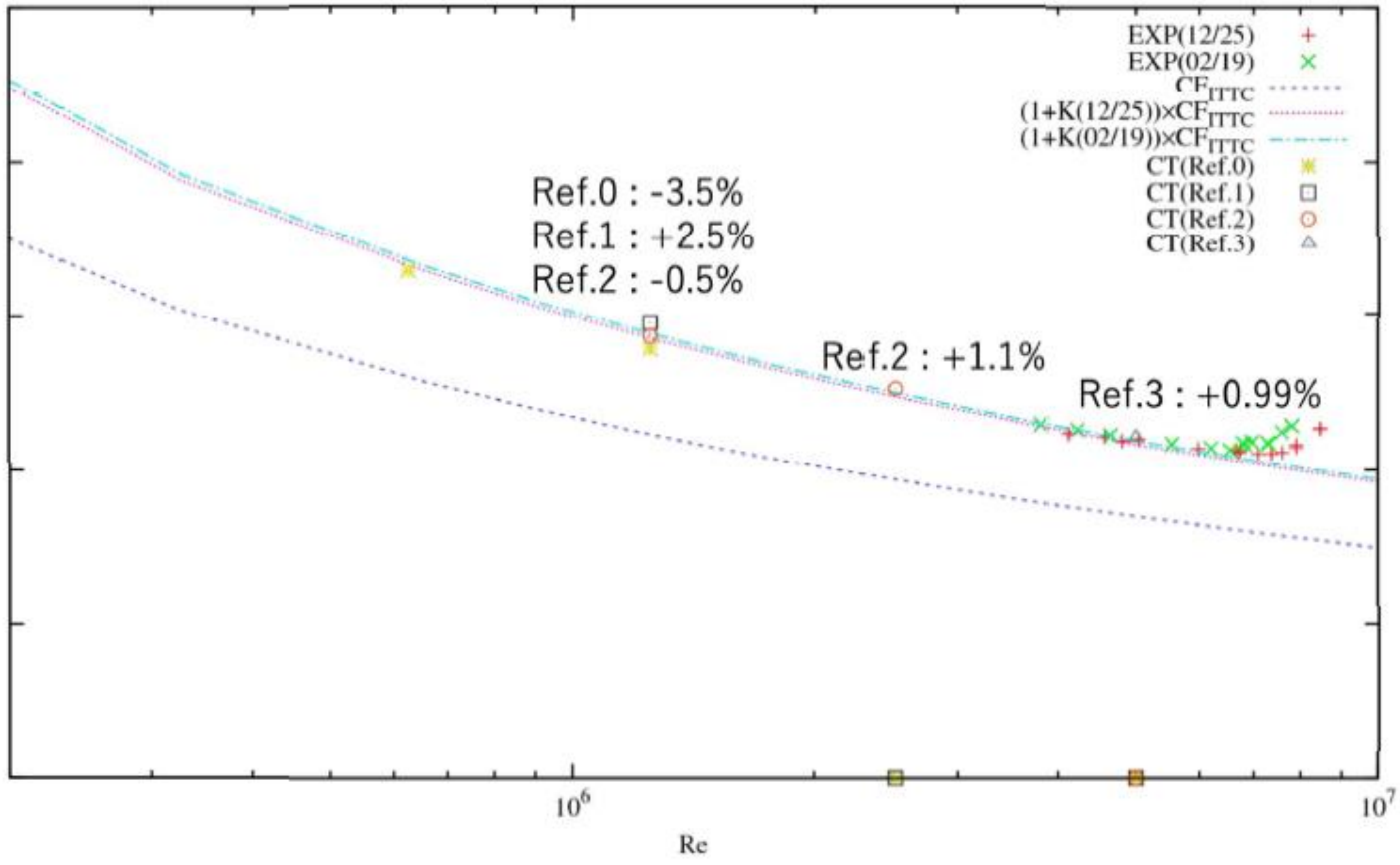
- A snapshot of computed vortices near hull surface



Courtesy of Shipbuilding Research Centre of Japan

Wall-Resolved LES for Another Vessel (cont'd)

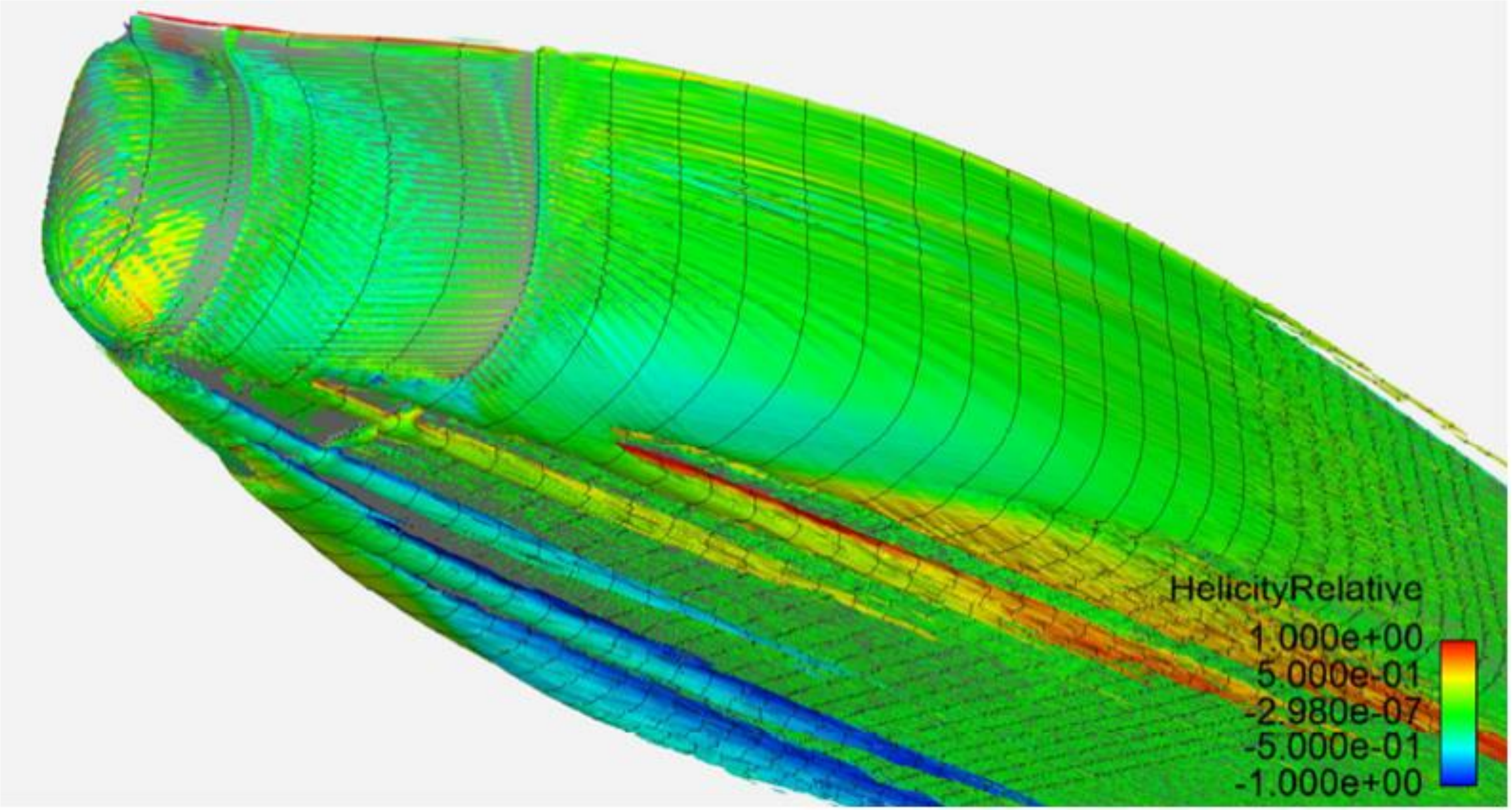
- Refined-mesh computation predicted resistance with less than 1% error



Courtesy of Shipbuilding Research Centre of Japan

HPC will also Provide New Insight (cont’d)

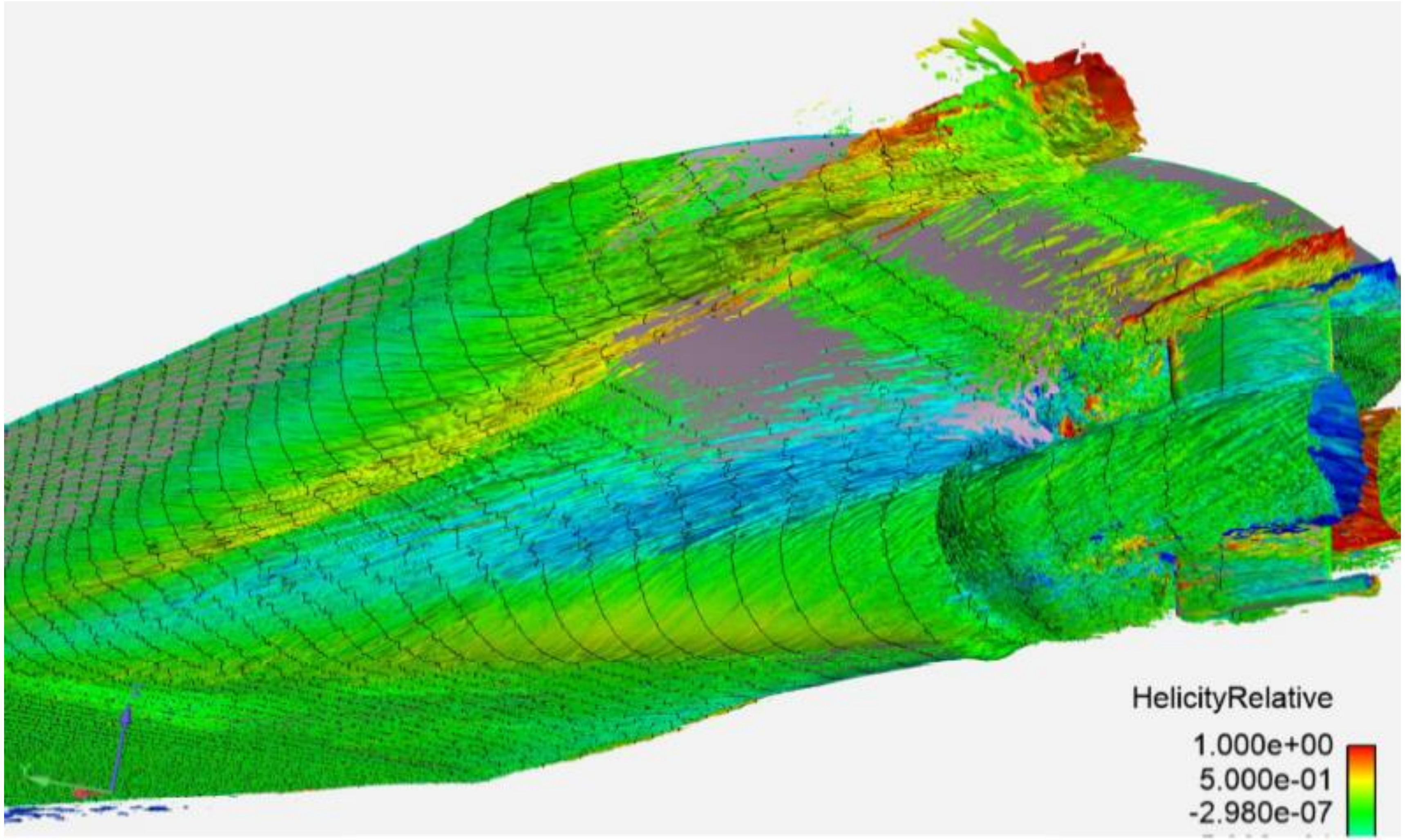
- A large-scale vortices identified (bow side).



Courtesy of Shipbuilding Research Centre of Japan

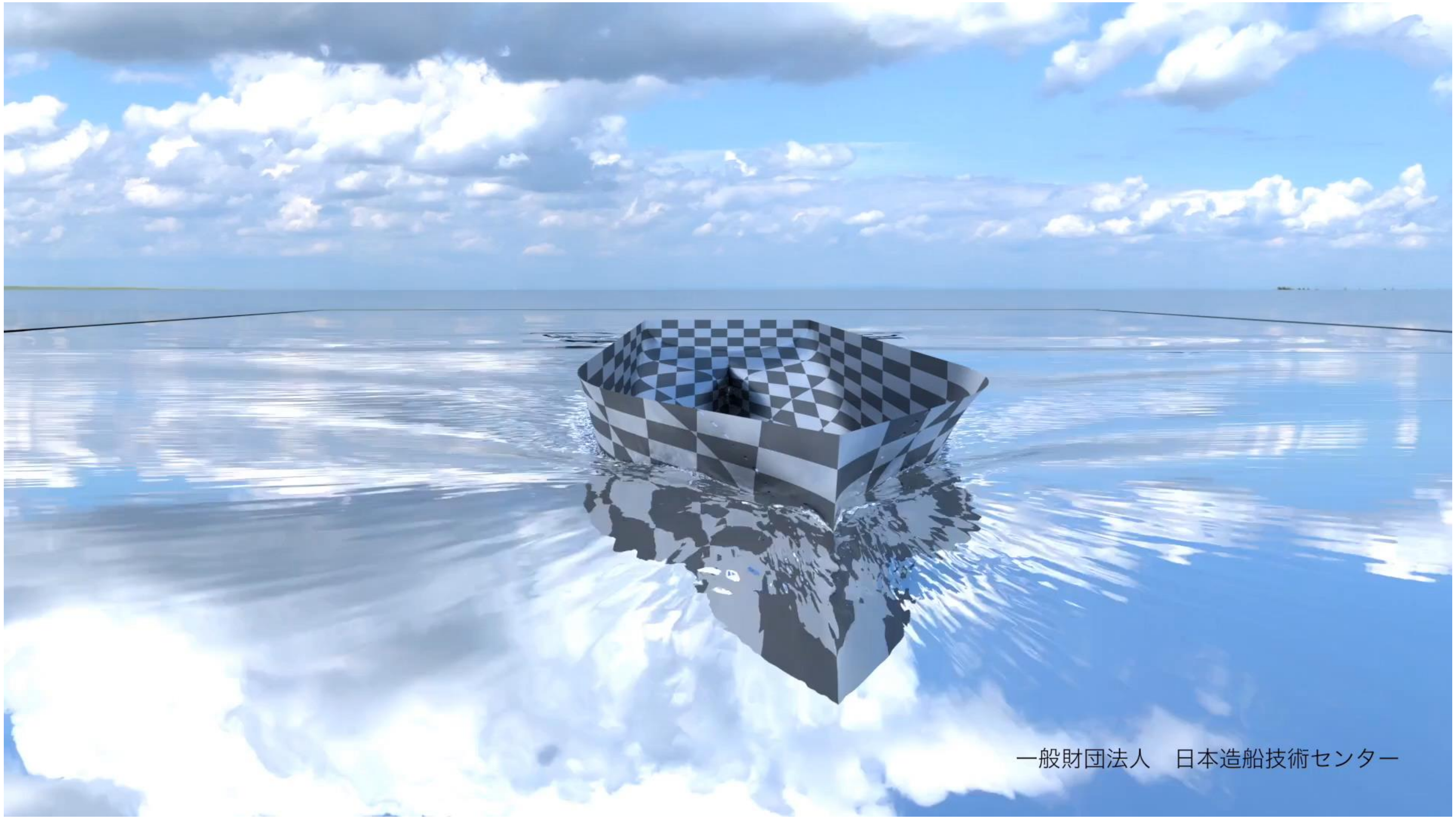
HPC will also Provide New Insight (cont'd)

- A large-scale vortices identified (stern side).

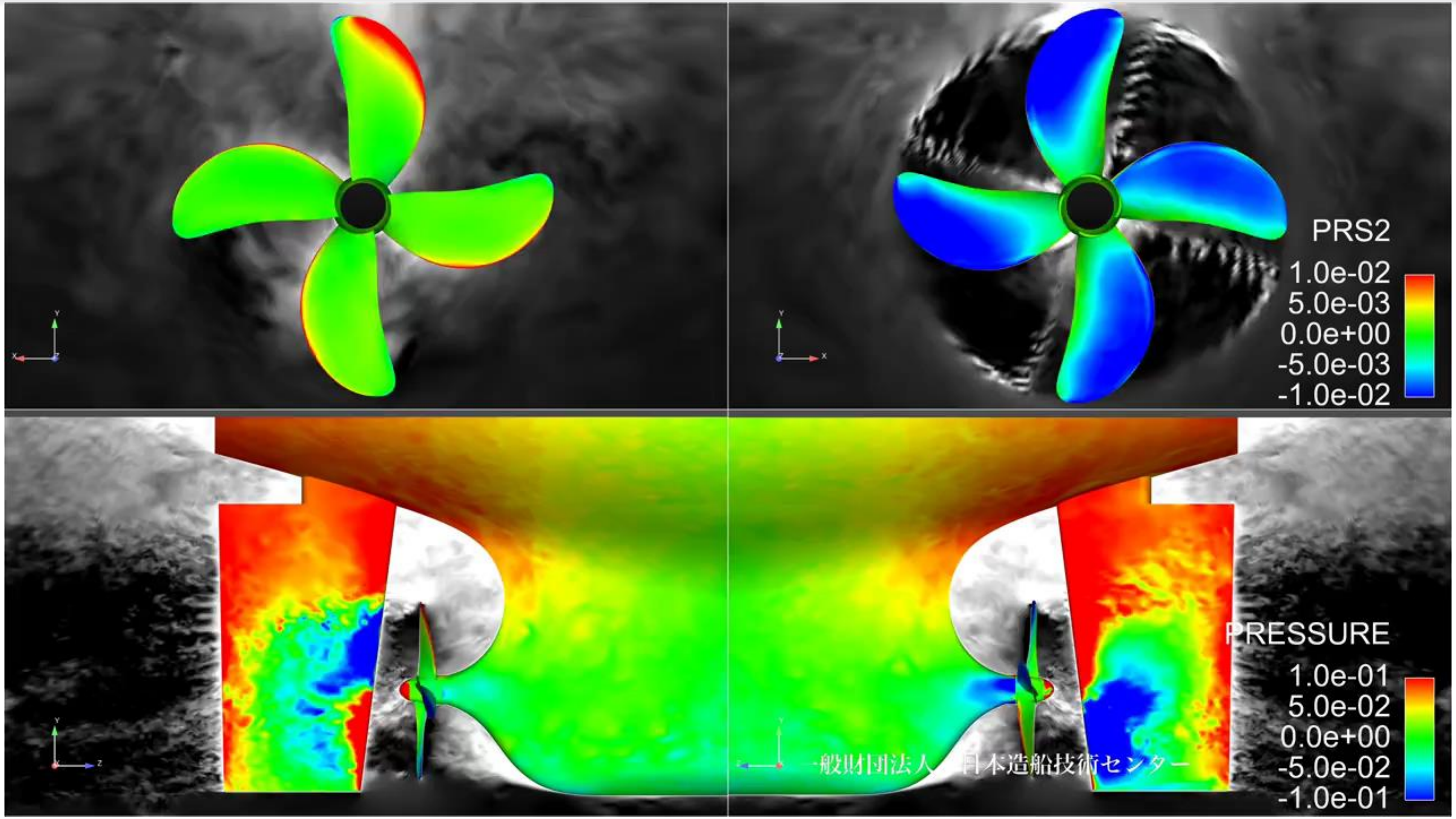


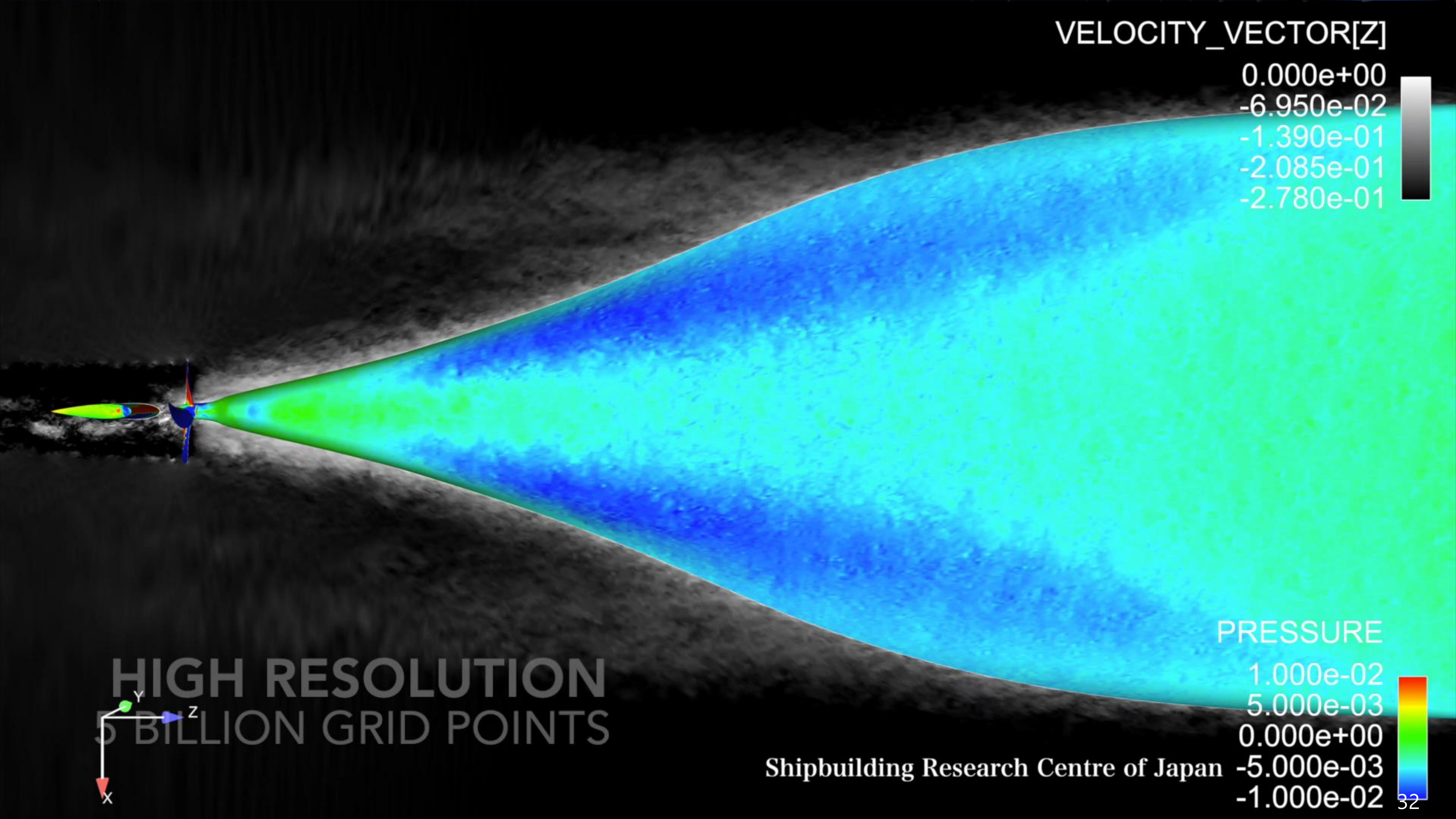
Courtesy of Shipbuilding Research Centre of Japan

Prediction of Wave-making Resistance



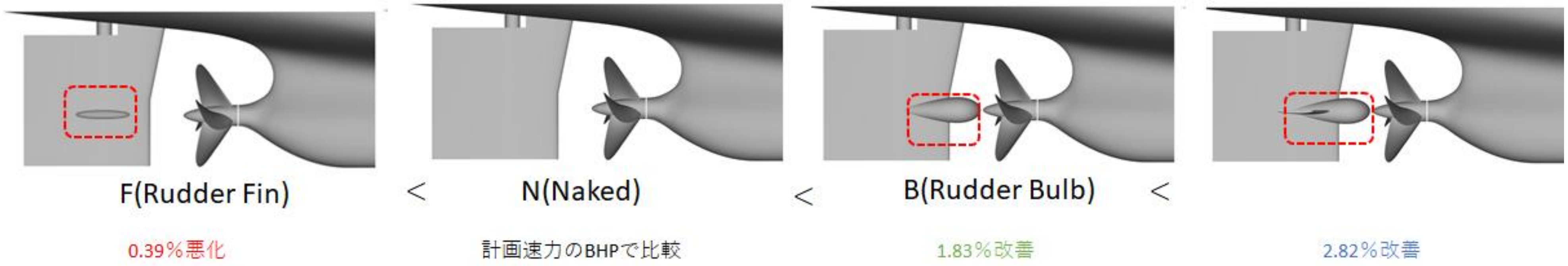
Self-propulsion Test for KVLCC2 Vessel

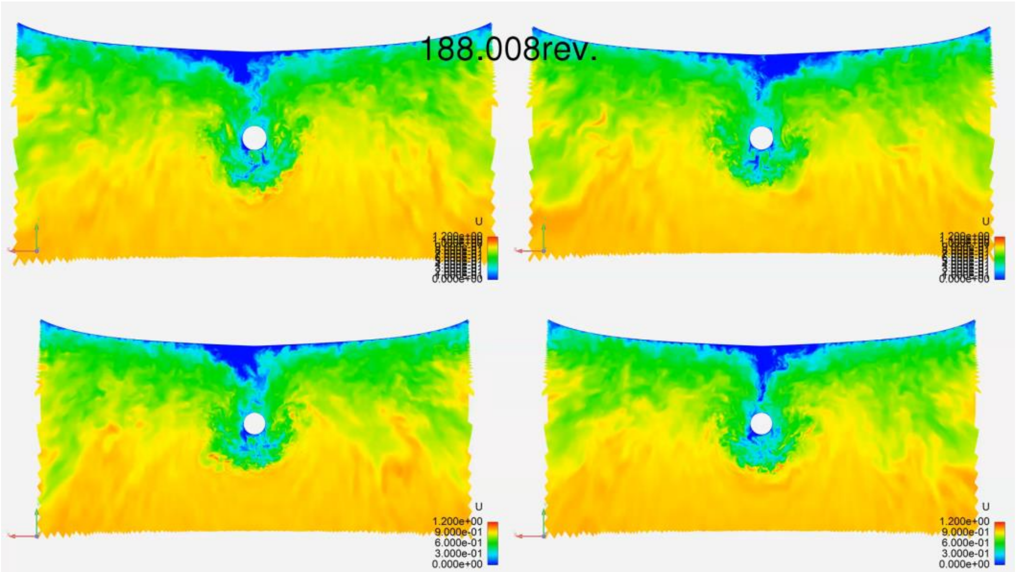


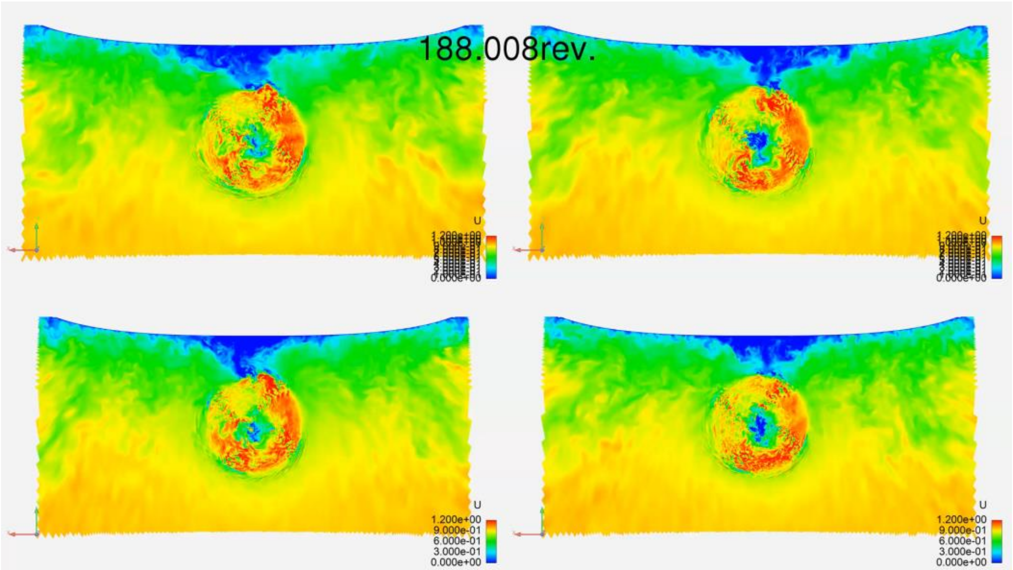


VELOCITY_VECTOR[Z]
0.000e+00
-6.950e-02
-1.390e-01
-2.085e-01
-2.780e-01
PRESSURE
1.000e-02
5.000e-03
0.000e+00
-5.000e-03
-1.000e-02
HIGH RESOLUTION
5 BILLION GRID POINTS
Y
Z
X
Shipbuilding Research Centre of Japan

To Achieve a Better Propulsion Performance





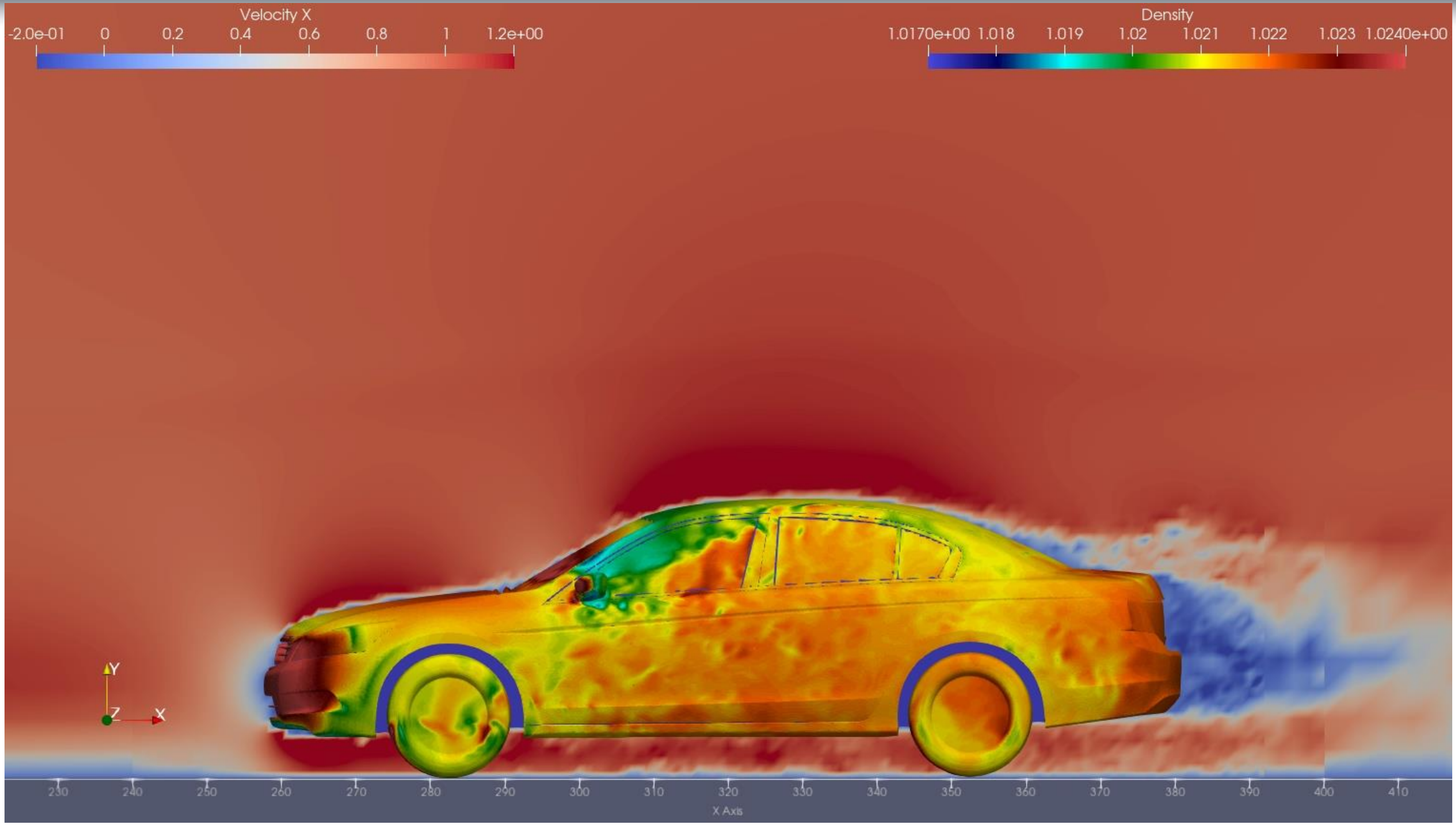


Applications to Automobile Aerodynamics and Aeroacoustics

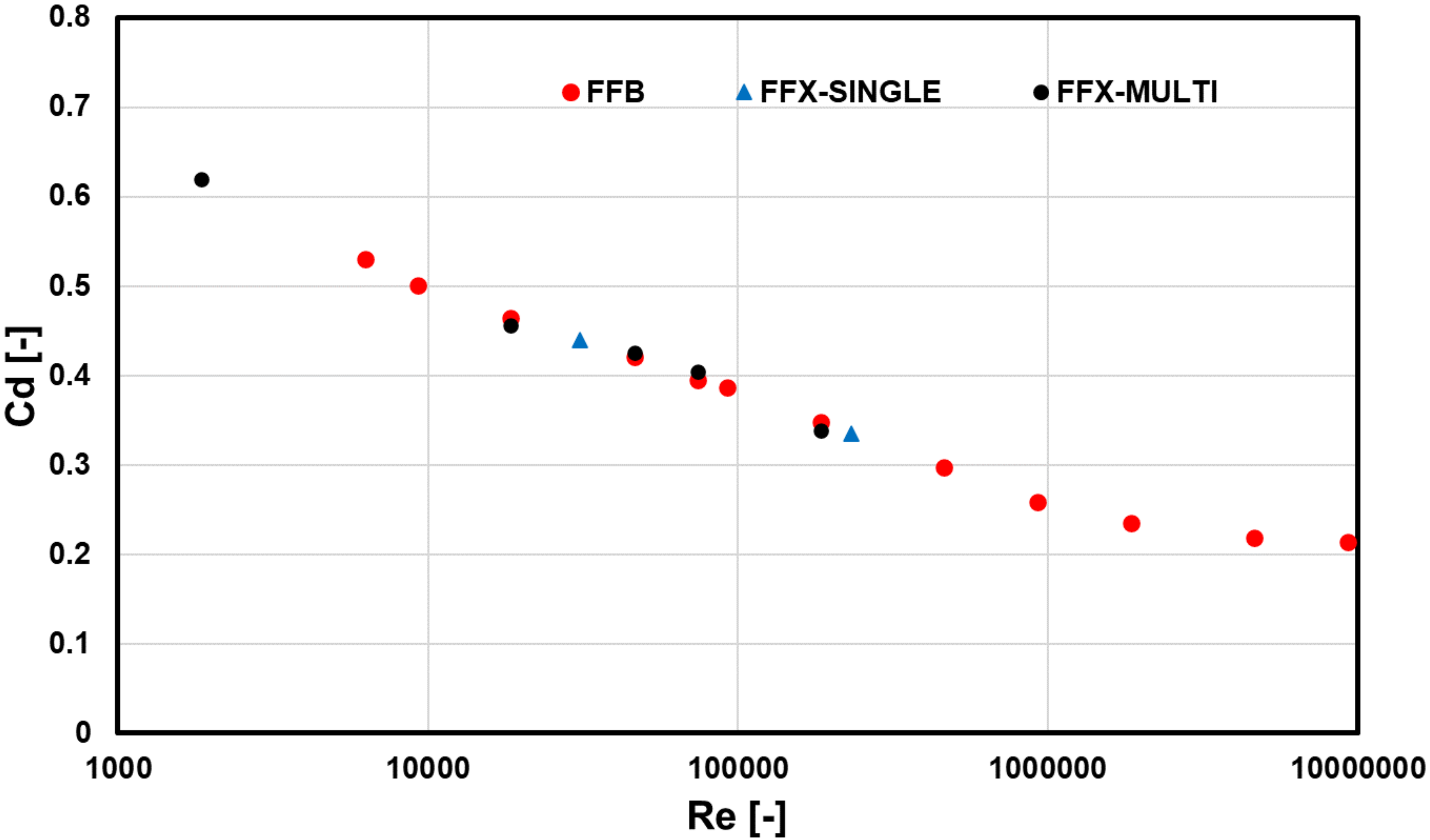
Numerical Wind-tunnel Tests for Automobile Aeroacoustics

Keiichiro IIDA, et al., SAE 2016 World Congress and Exhibition, 2016

Latest Results by FFX (LBM code)

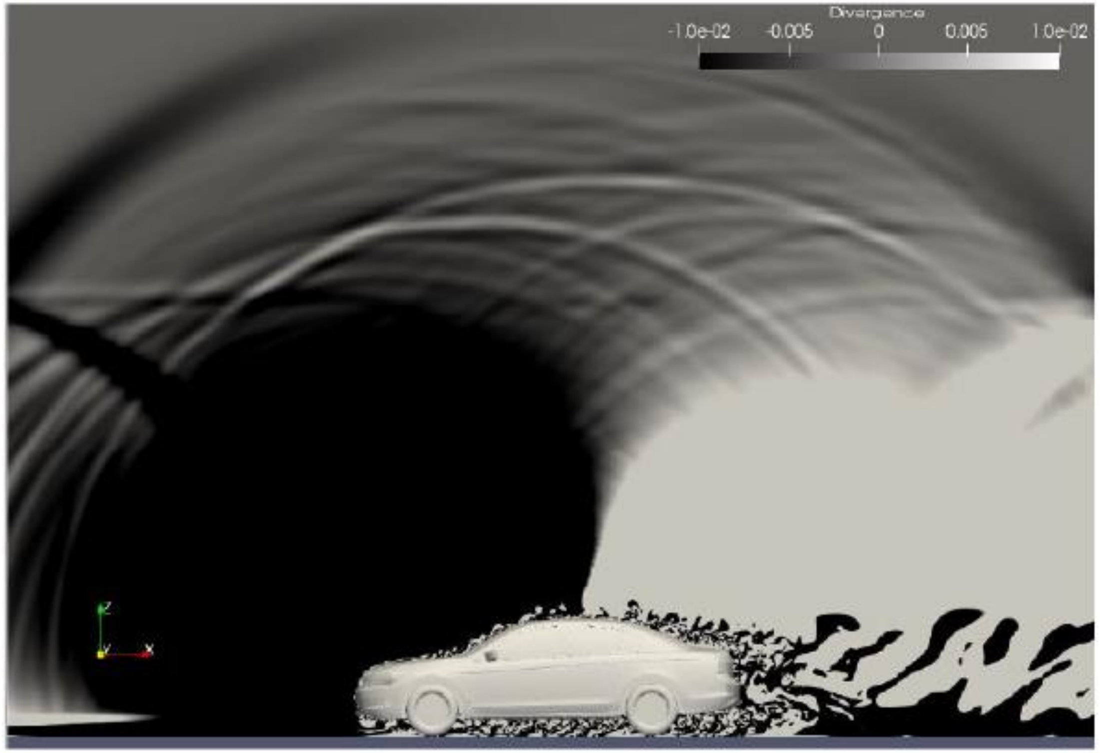


Navier-Stokes Solver and LBM Solver

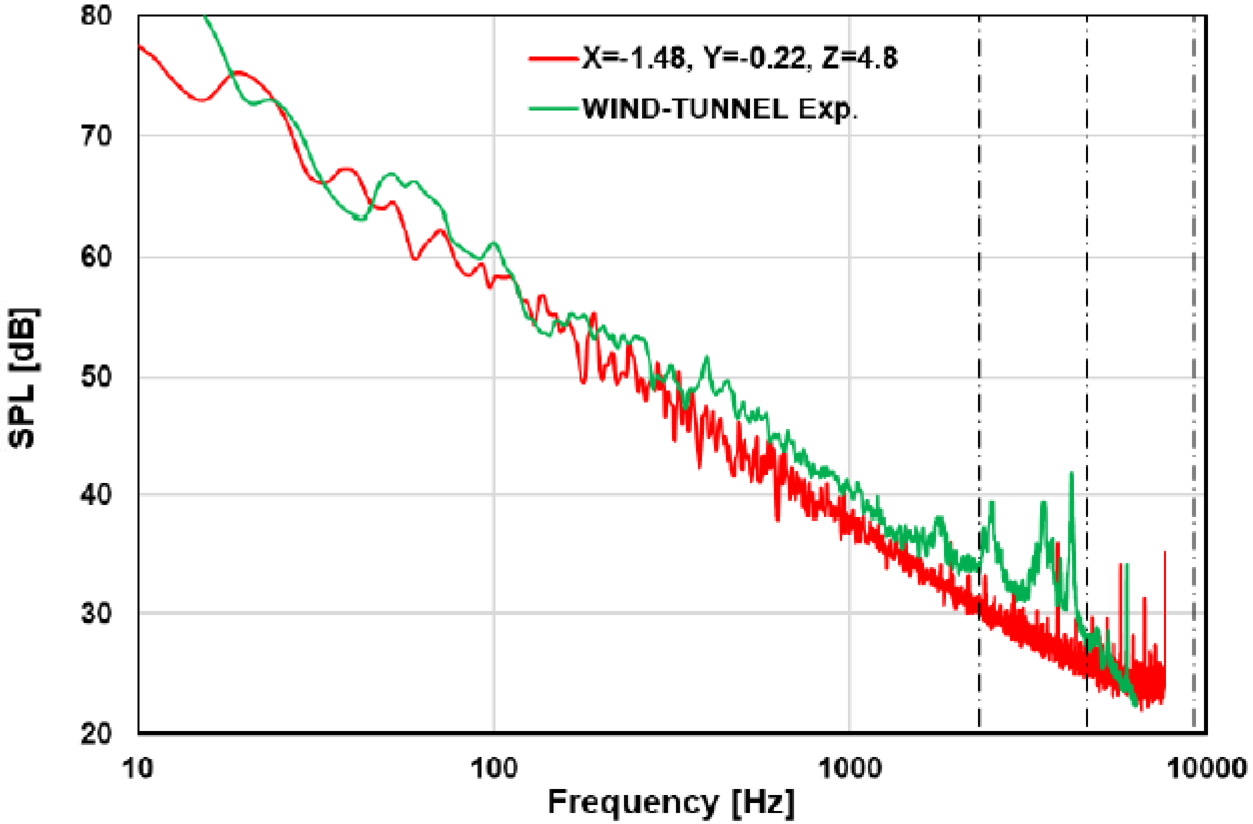


Drag coefficients predicted by Navier-Stokes Solver (FFB) and Lattice Boltzmann Solver (FFX)

Comparison with Wind-tunnel Test (LBM Solver)



Instantaneous hydro-dynamical and acoustical fields



Sound pressure level compared with wind-tunnel test

Applications to Fundamental Research

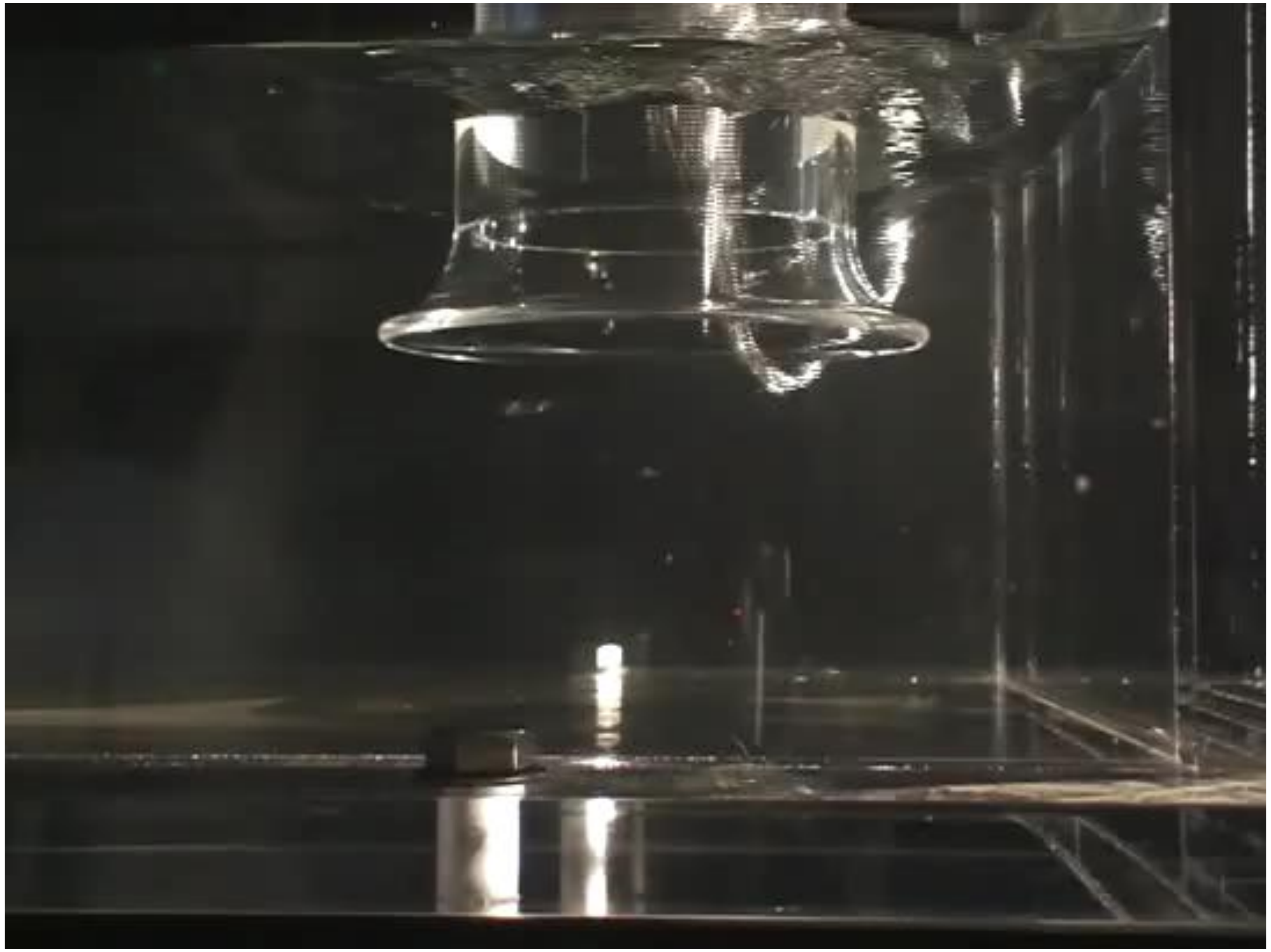
Numerical Investigations on Suction Vortices in a Pump Sump

-their origin, formation and dynamics-

Yoshinobu YAMADE, et al., Journal of Fluids Engineering, 2020

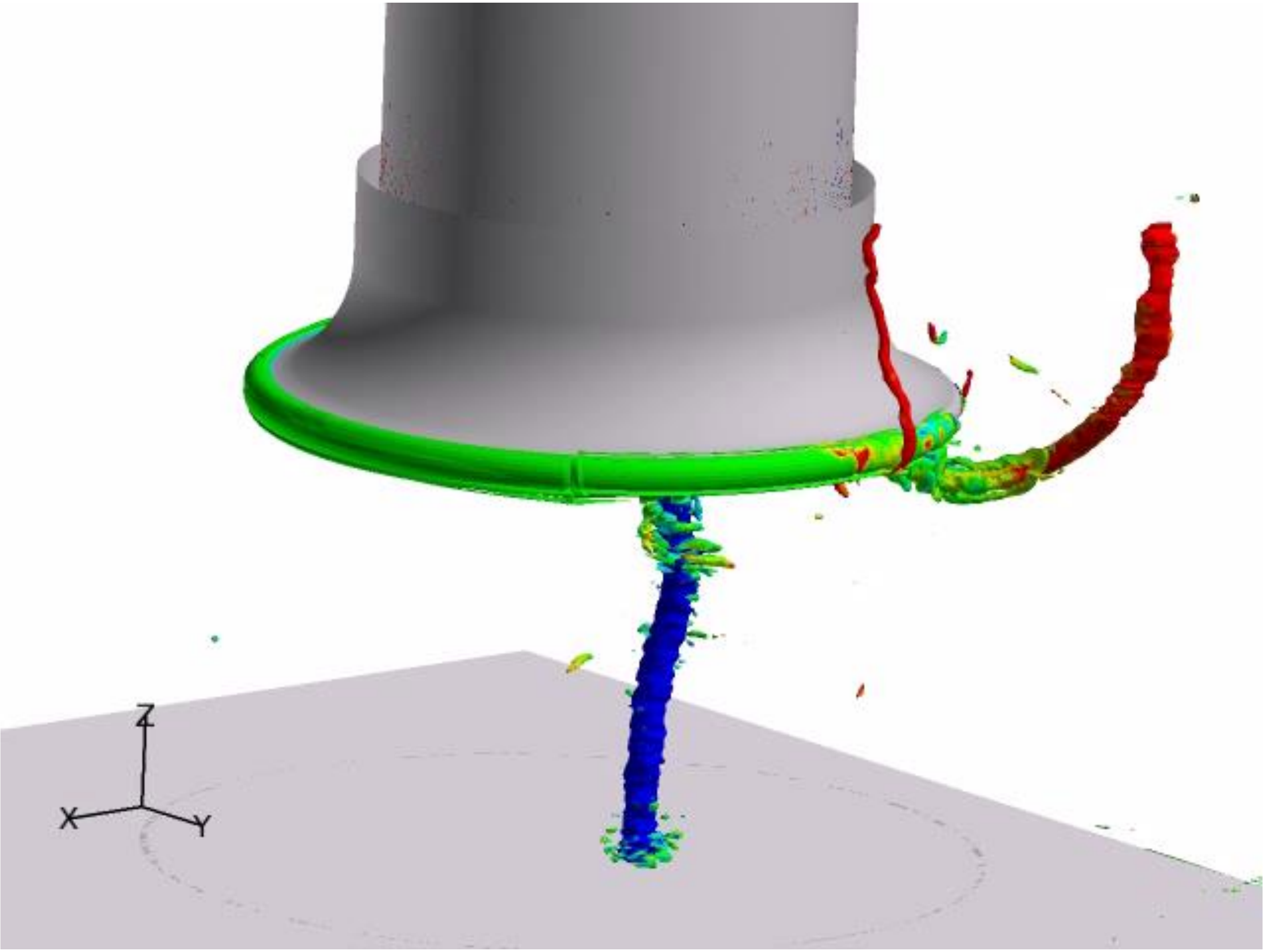
Suction Vortices in a Pump Sump

- **Their origin, formation and dynamics**



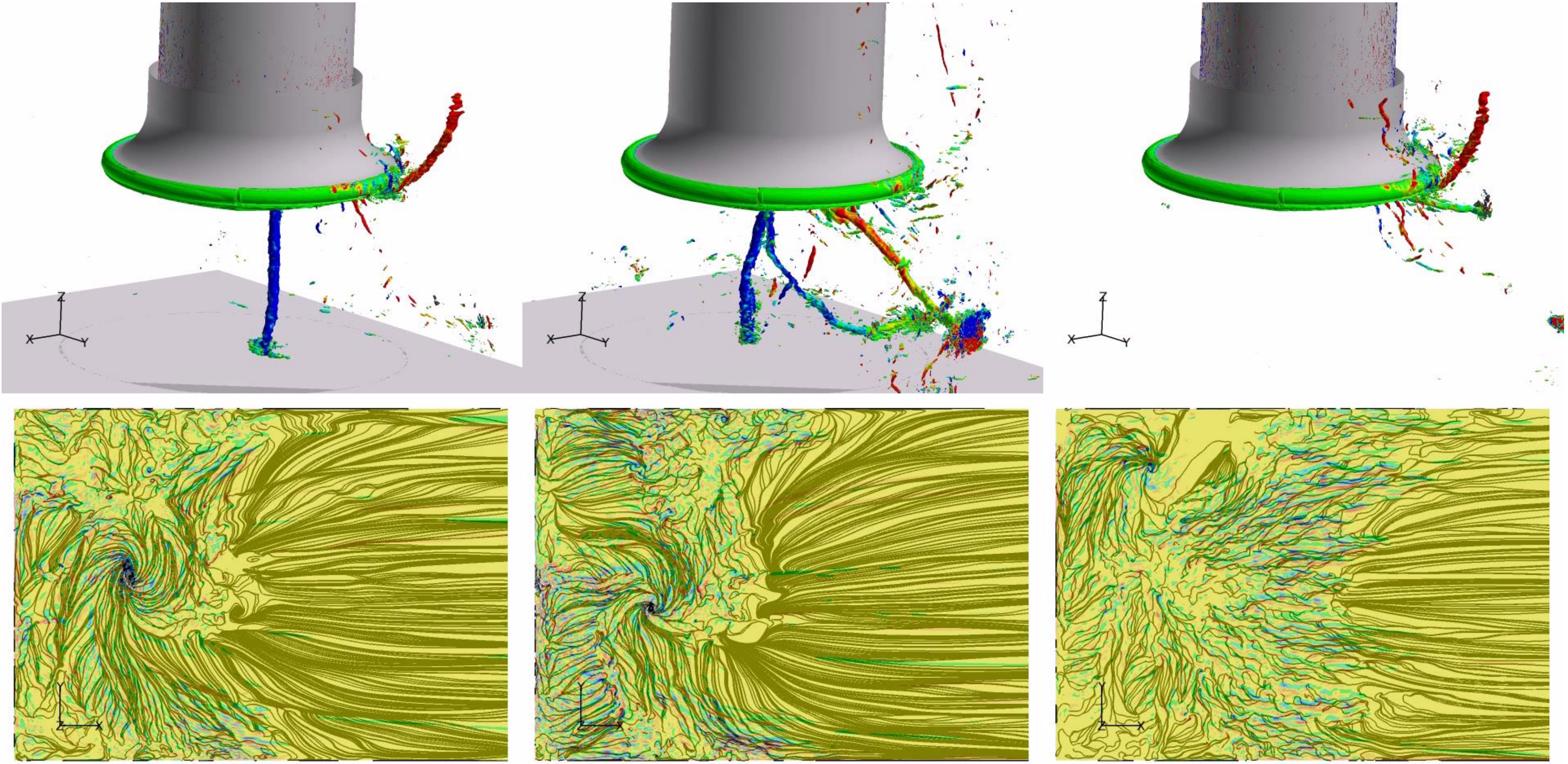
Courtesy of Prof. Matsui of
Yokohama National University

Wall-resolving LES of Suction Vortices



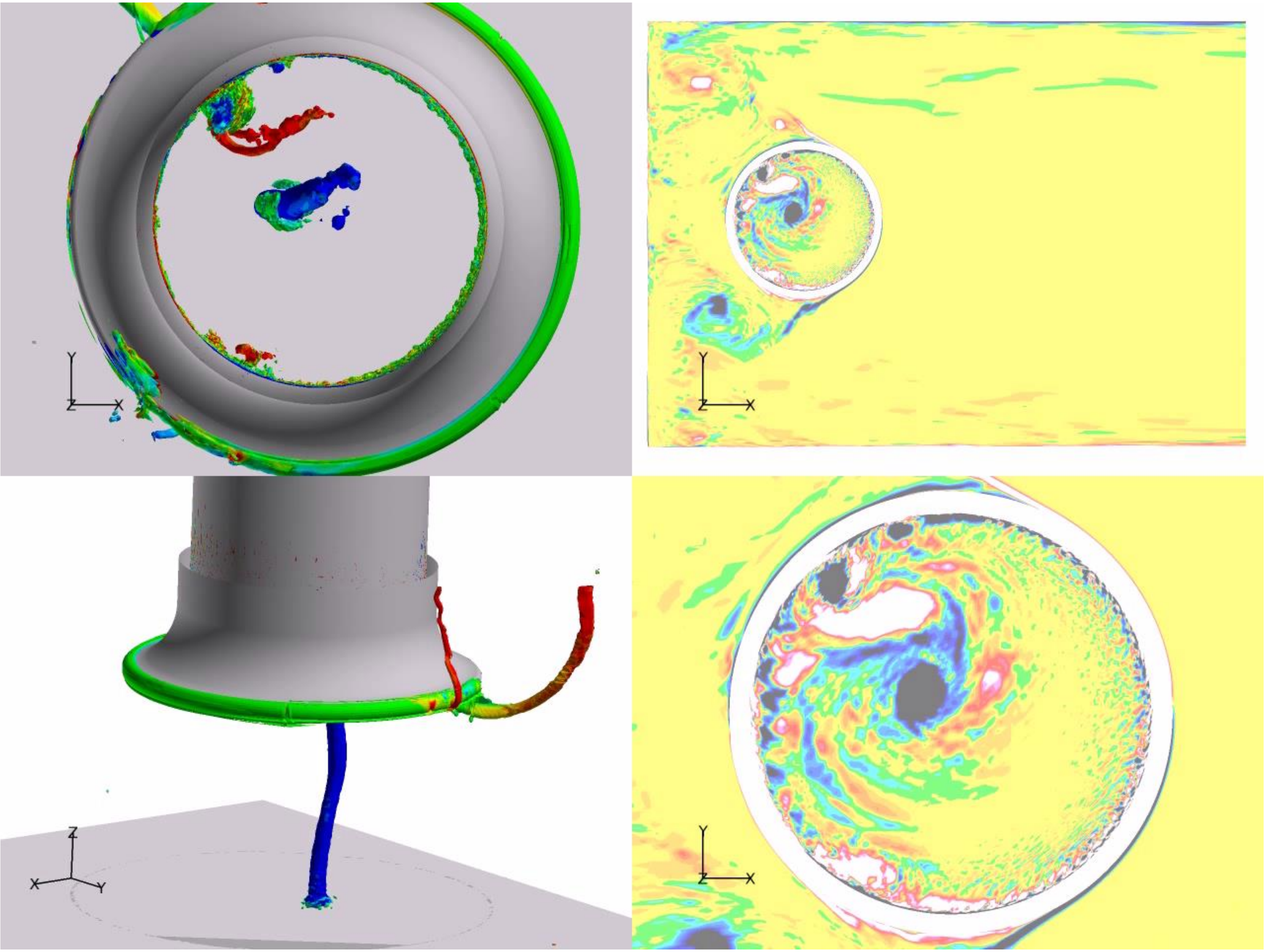
Origin of Submerged Vortices

- **Computations with different wall-boundary conditions**

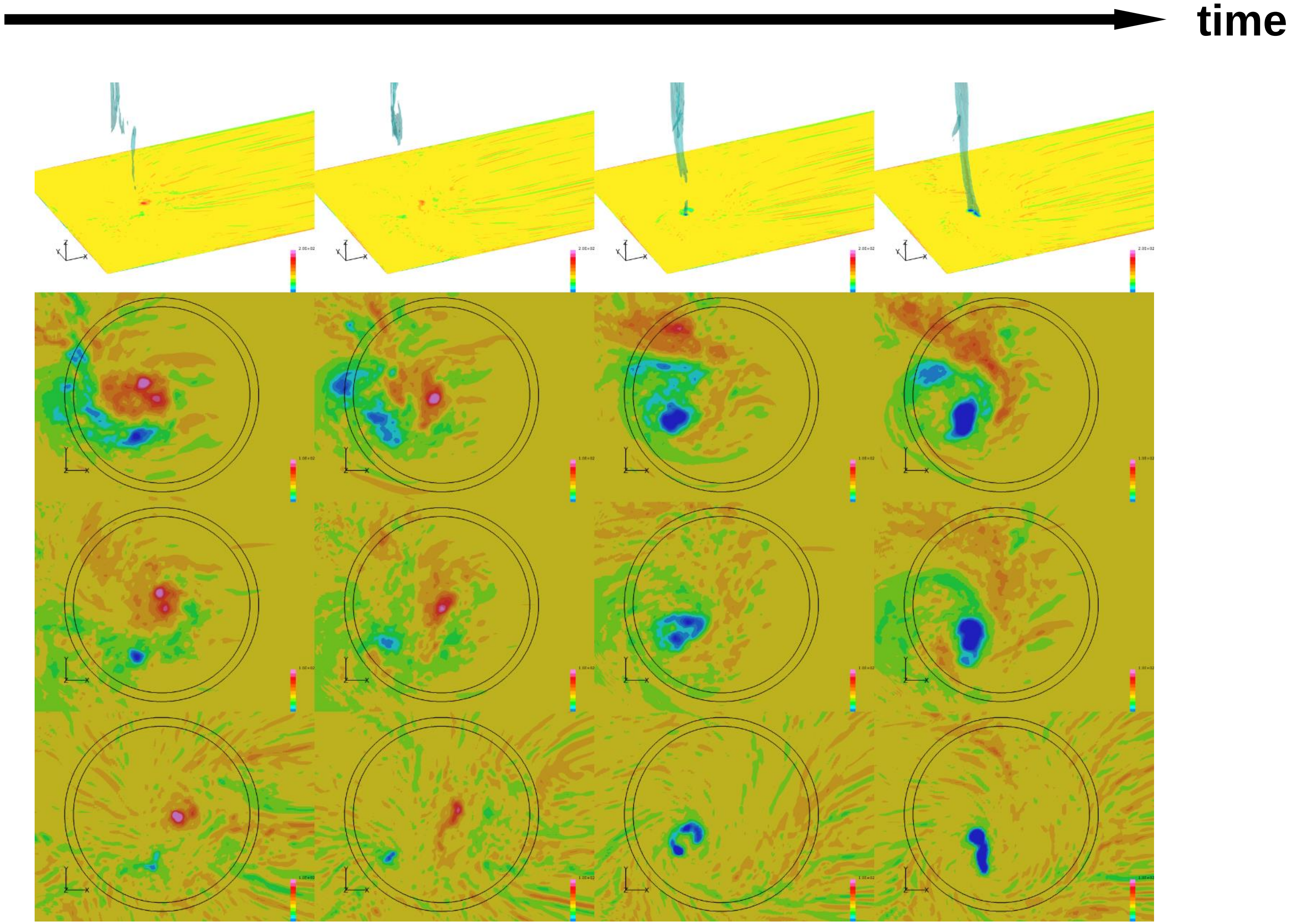


Turbulent boundary layer **Laminar boundary layer** **No boundary layer**

Origin of Air-entrained Vortices



Formation of Submerged Vortices



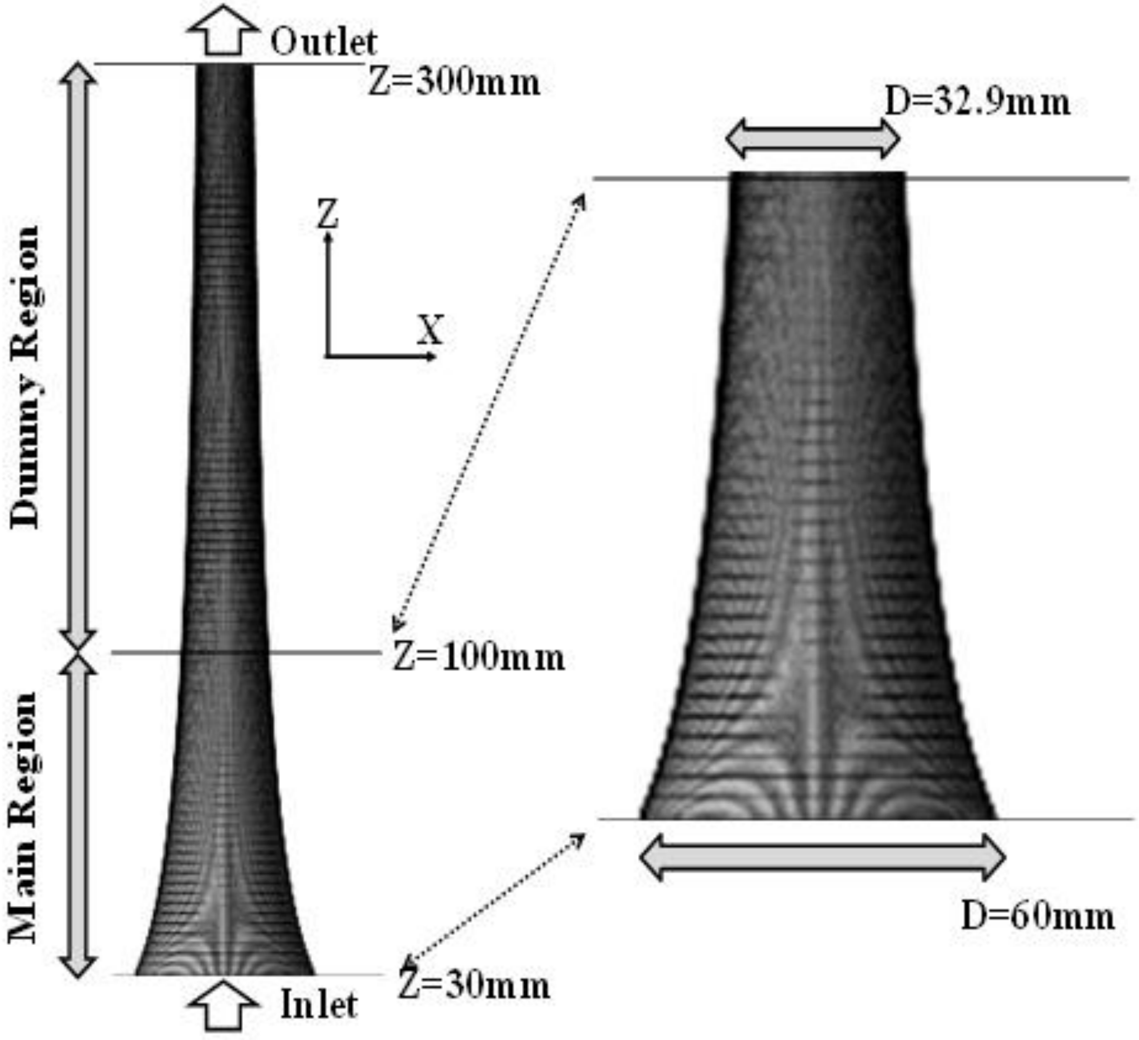
Development of vertical vorticity in time

80 mm above floor

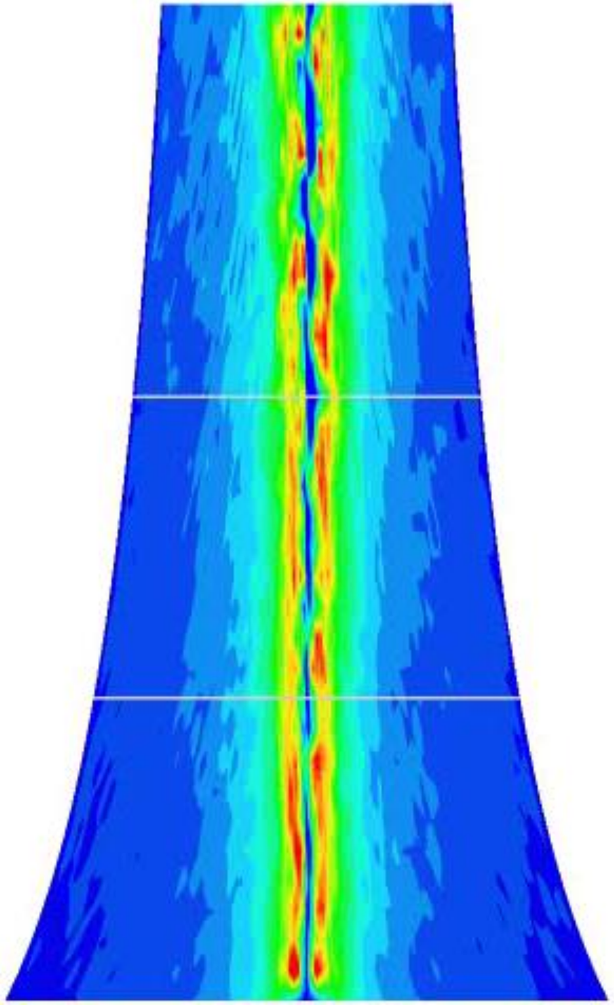
40 mm above floor

1 mm above floor

Dynamics of Submerged Vortices

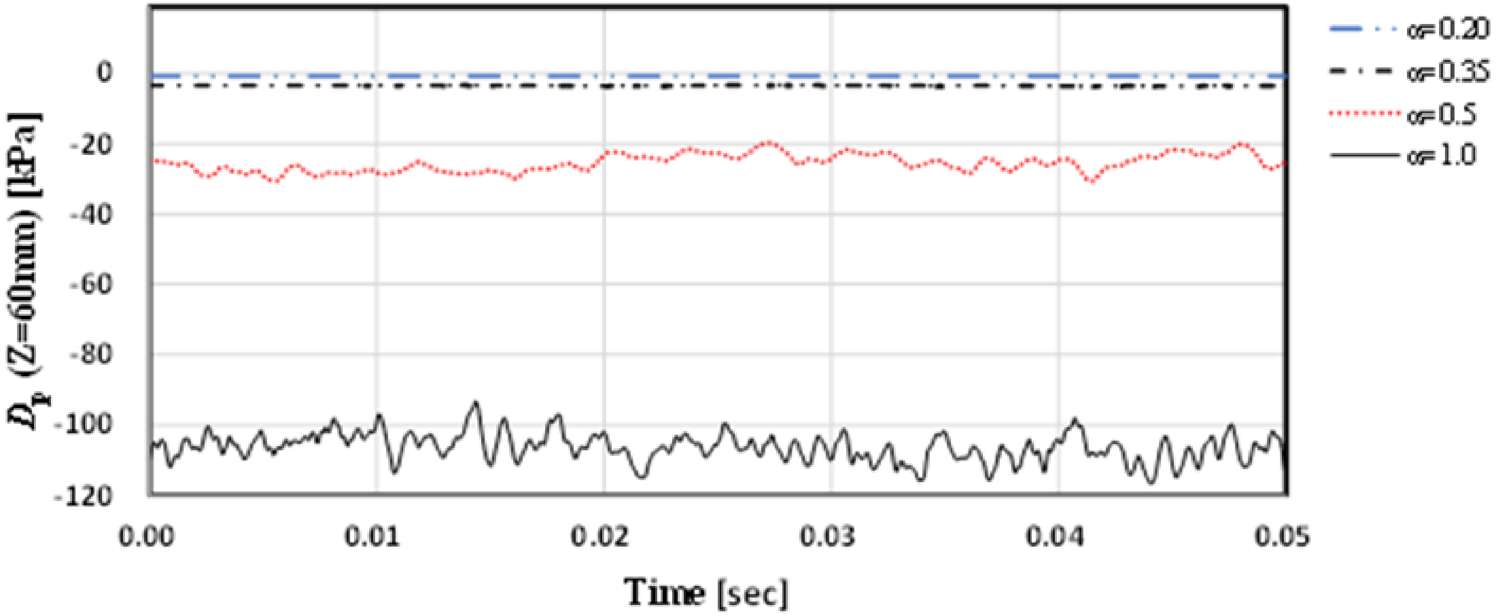


Simplified high-resolution computational model

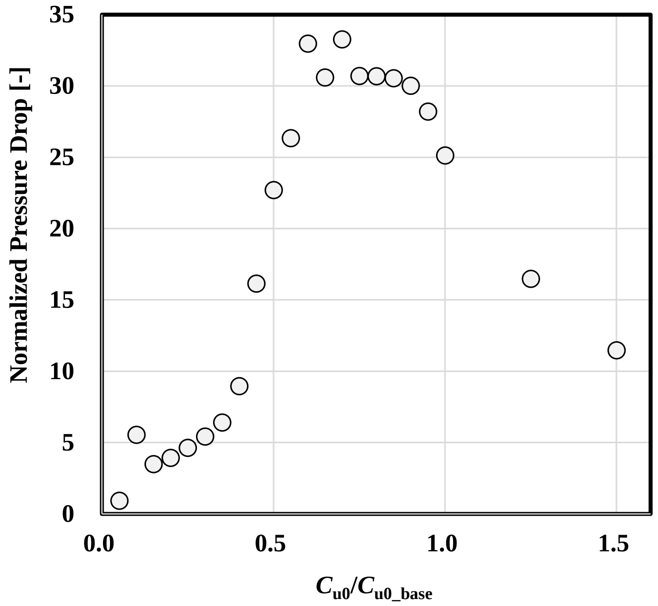


Variation of vertical velocity in time and space

Effects of Swirl Number on Dynamics

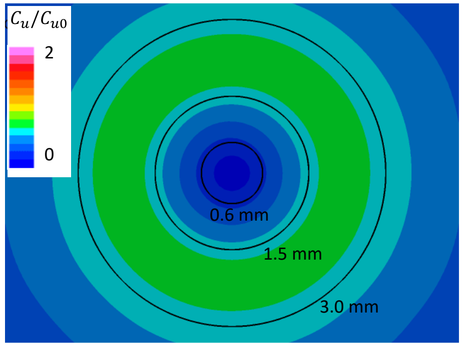


Variations of static-pressure drop in time

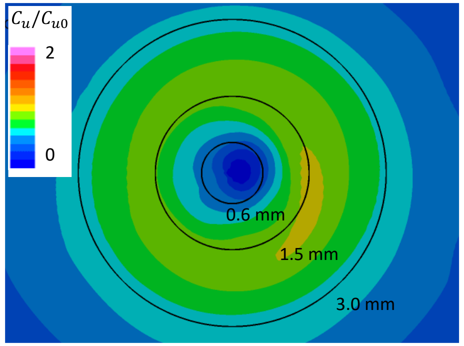


Normalized static-pressure drop

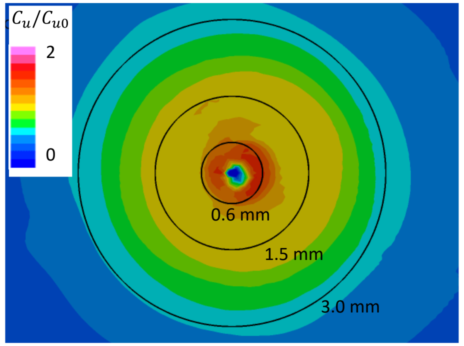
α=0.2



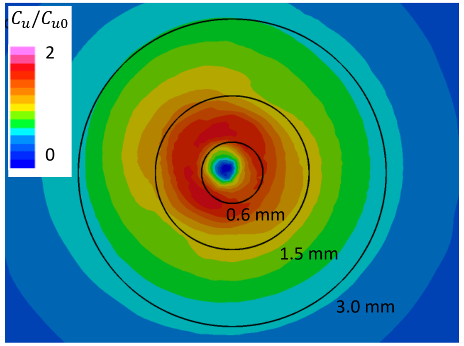
α=0.35



α=0. 5



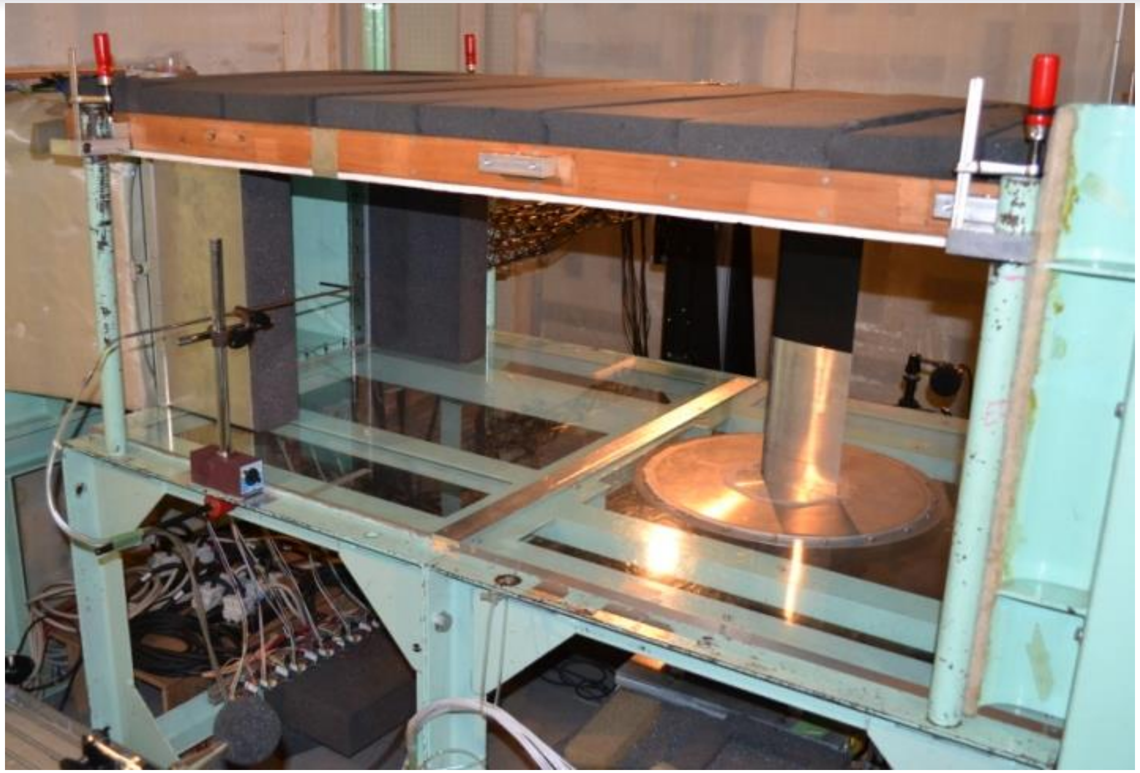
α=1.0



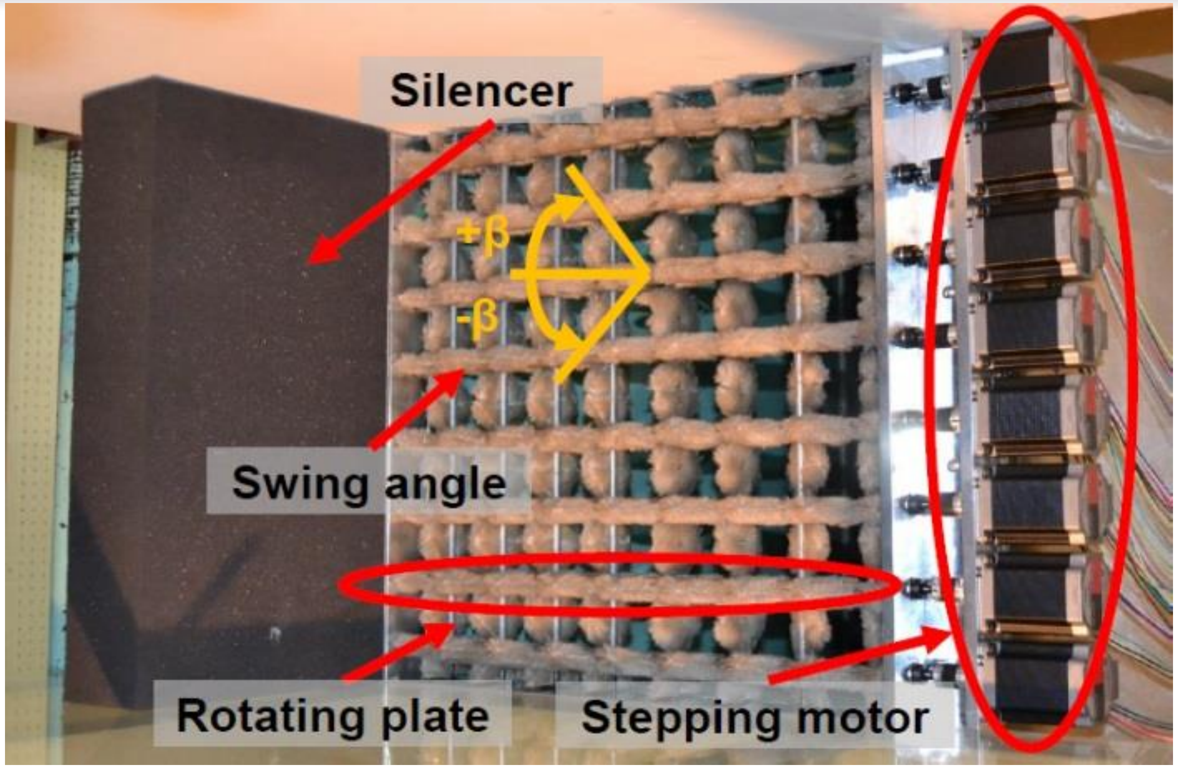
Sound Radiated from a Lifting Surface subjected to Inflow Turbulence

Noriaki KOBAYASHI, et al., Transactions of the JSME (in Japanese), 2020

Wind-tunnel Test with Turbulence Generator

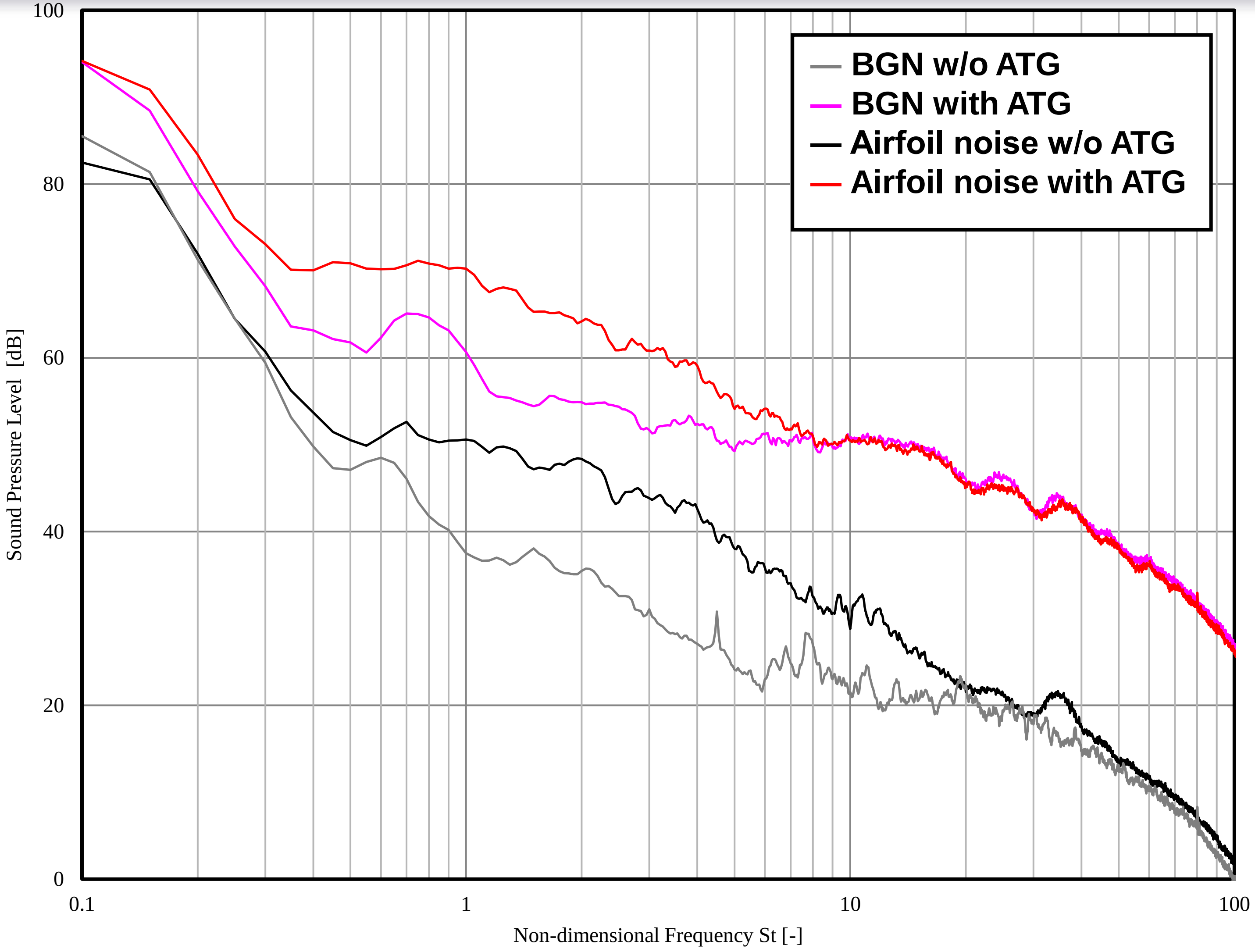


Test NACA0012 airfoil



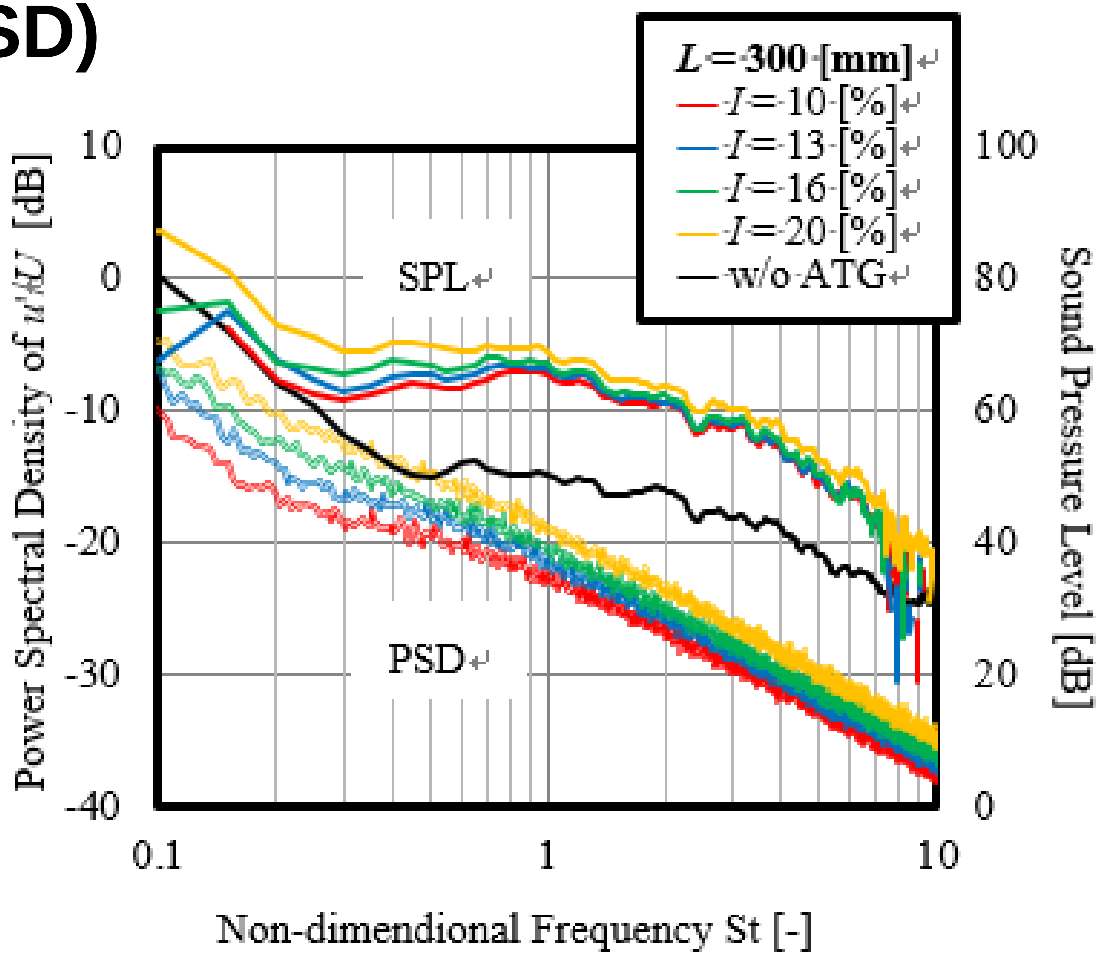
Active Turbulence Generator (ATG)

Sound Pressure Level measured in Wind-tunnel

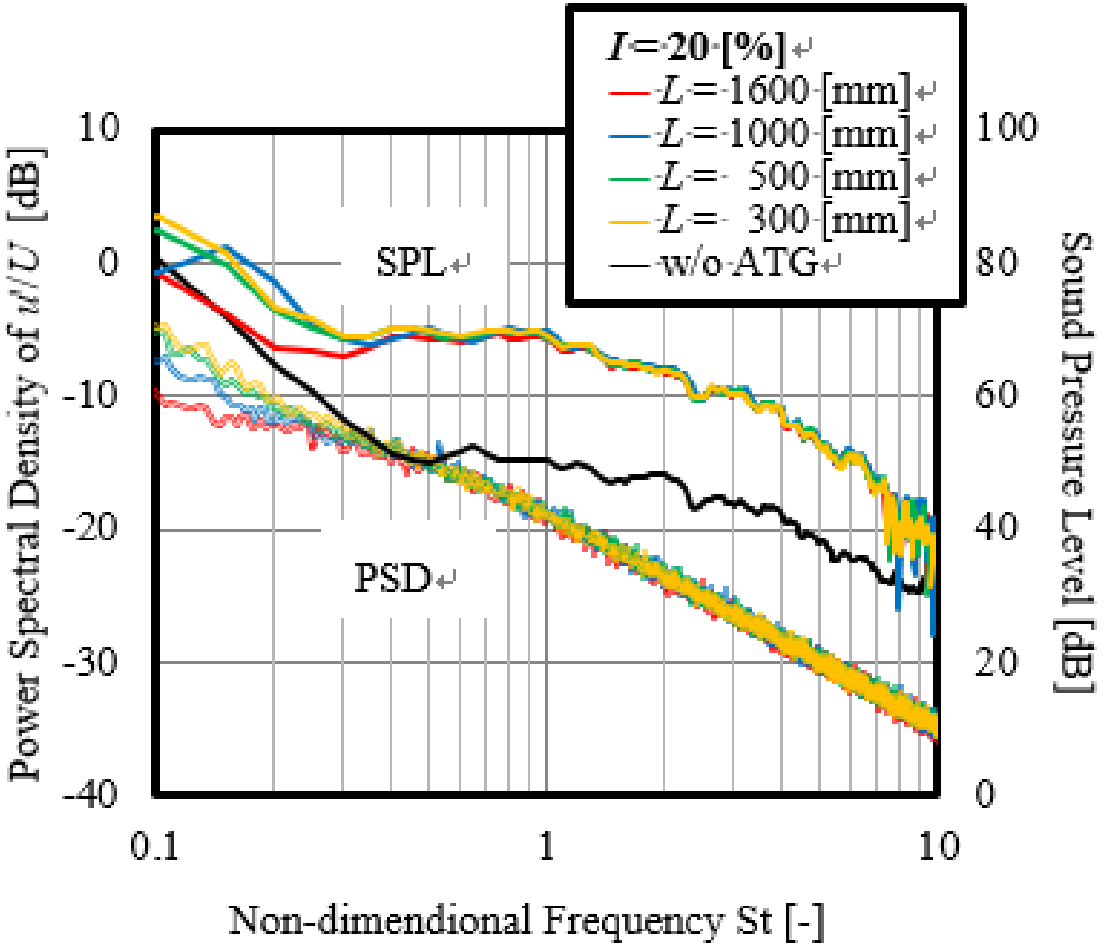


Effects of Turbulence Intensity and Length Scale

- **Measured sound pressure level (SPL) and velocity fluctuations (PSD)**



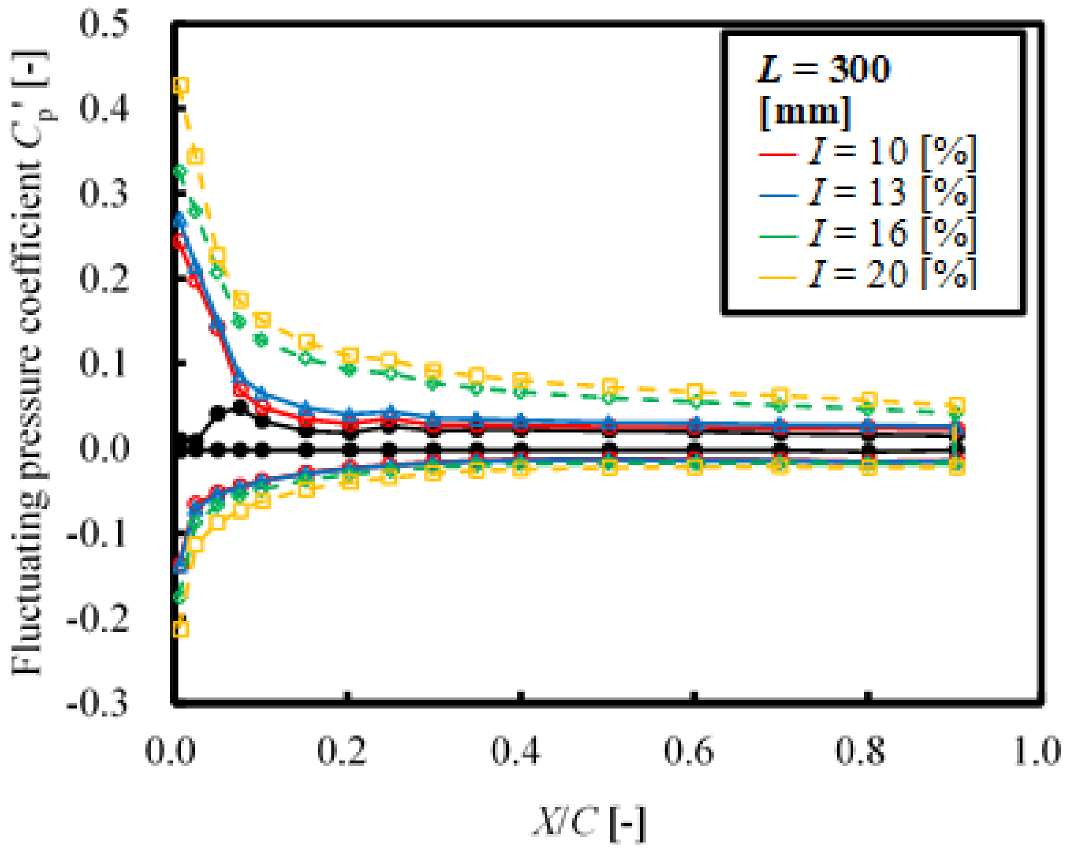
Varying turbulence intensity



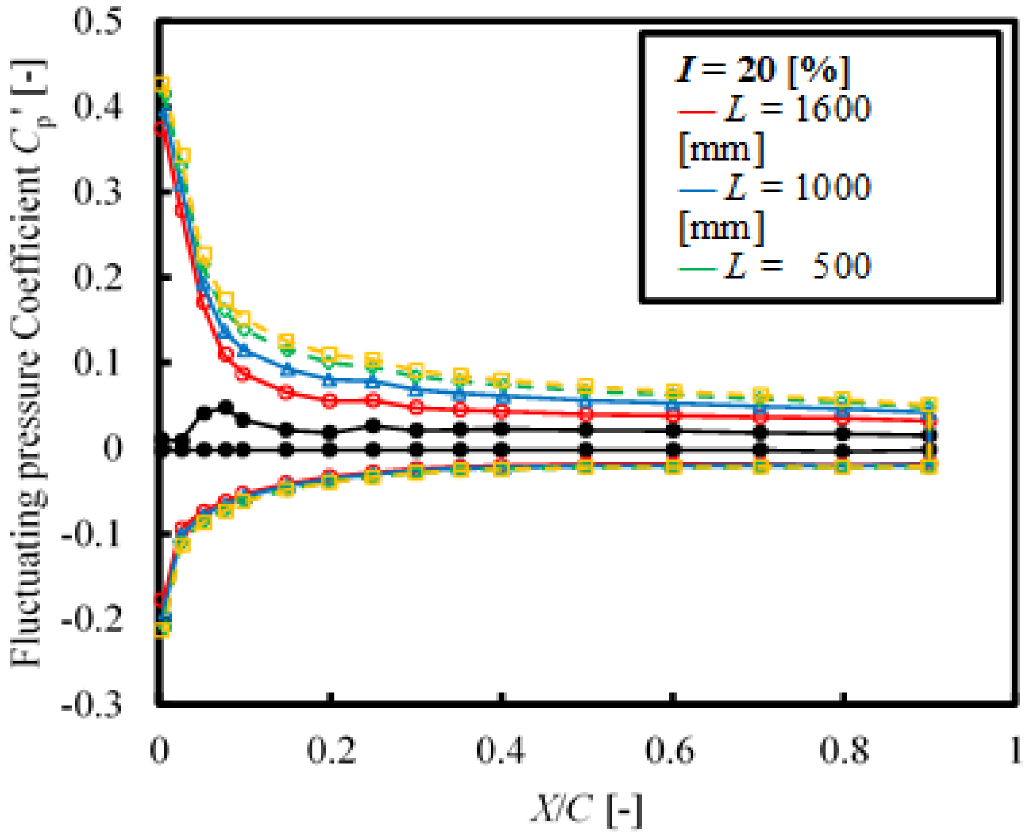
Varying turbulence length scale

Effects of Turbulence Intensity and Length Scale

- **Measured static-pressure fluctuations on airfoil surface**

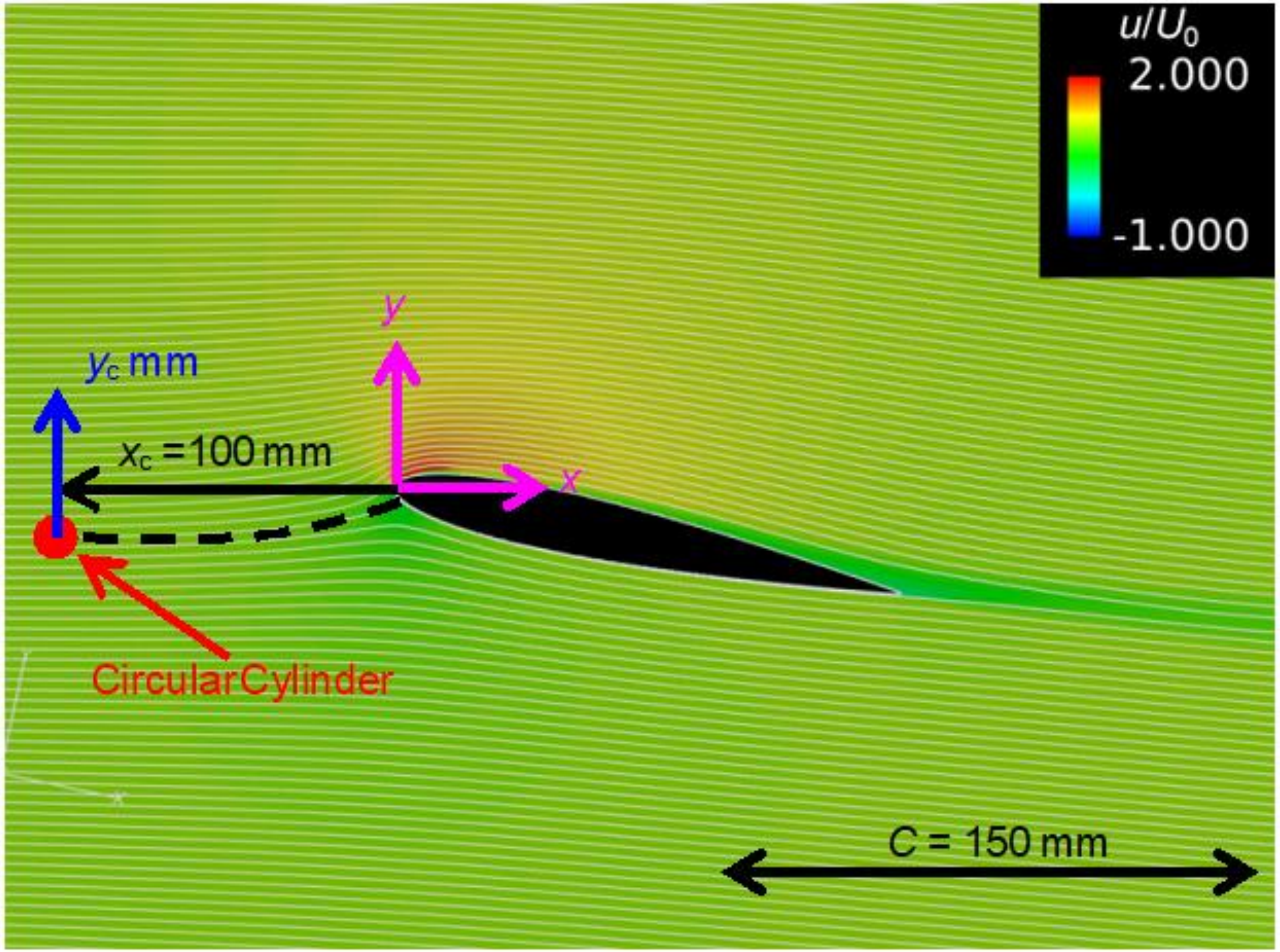


Varying turbulence intensity

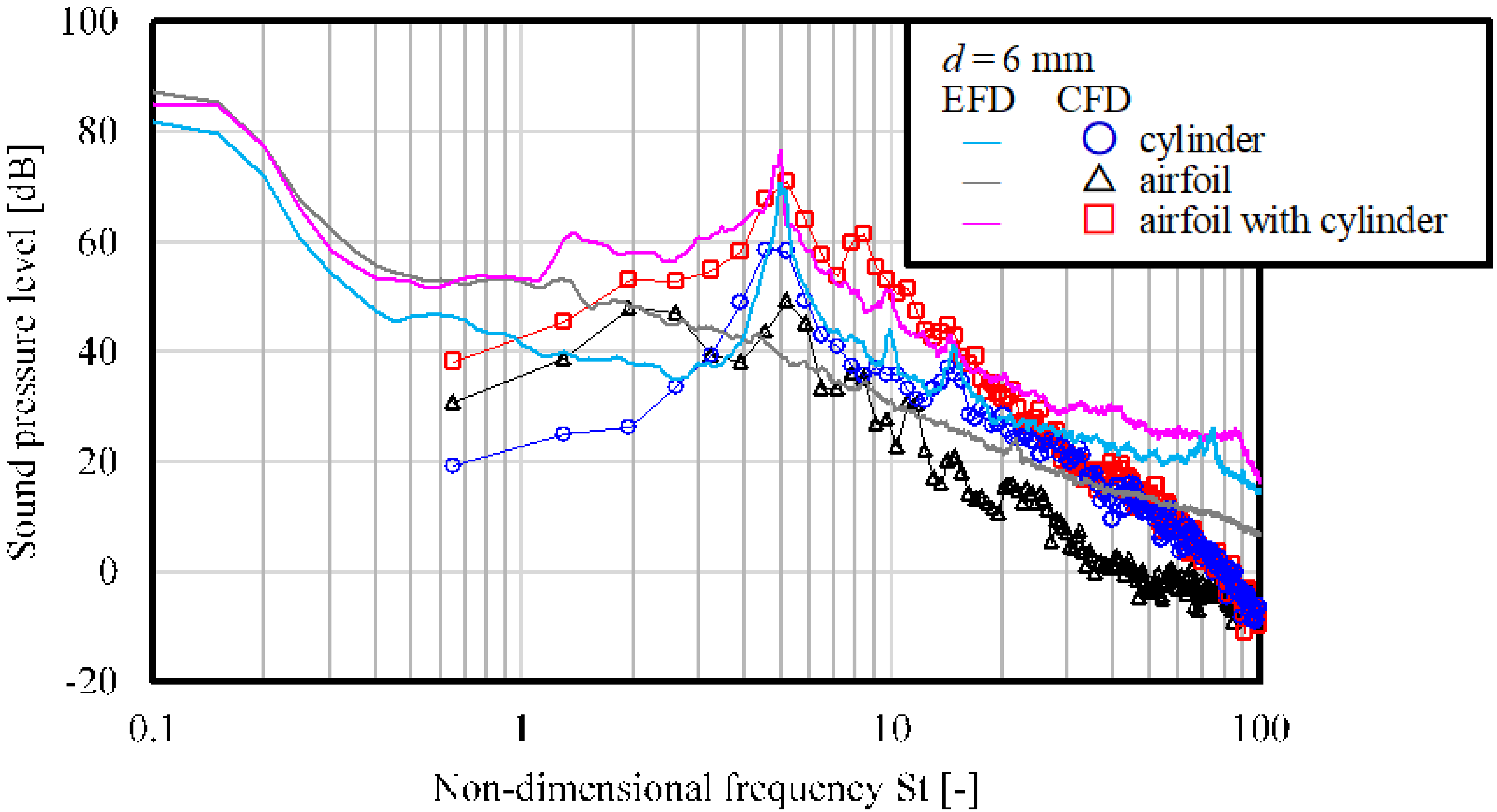


Varying turbulence length scale

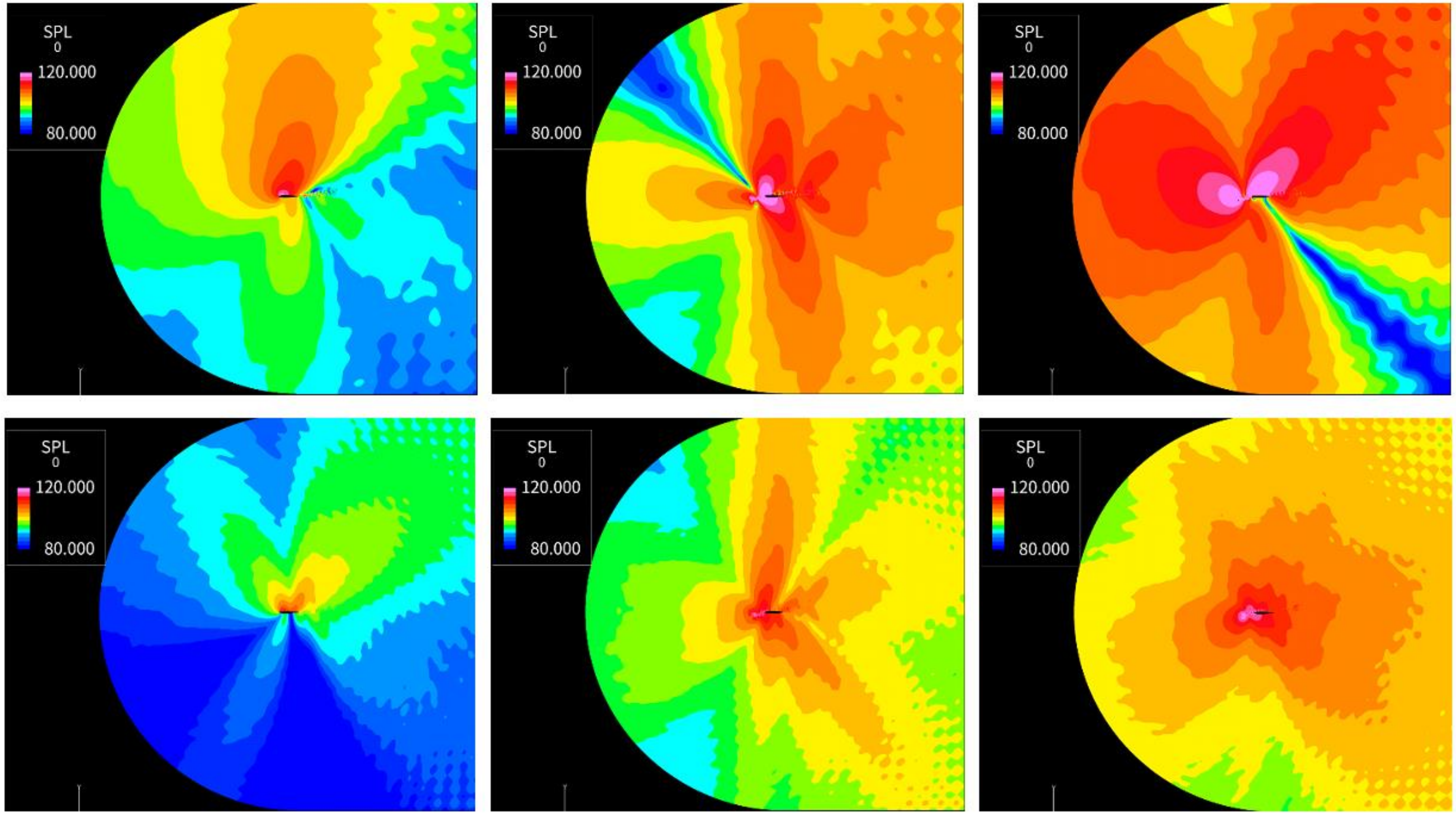
Airfoil subjected to Circular-cylinder Wake



Comparison of Measured and Predicted SPL



Predicted Sound Fields with/without Cylinder

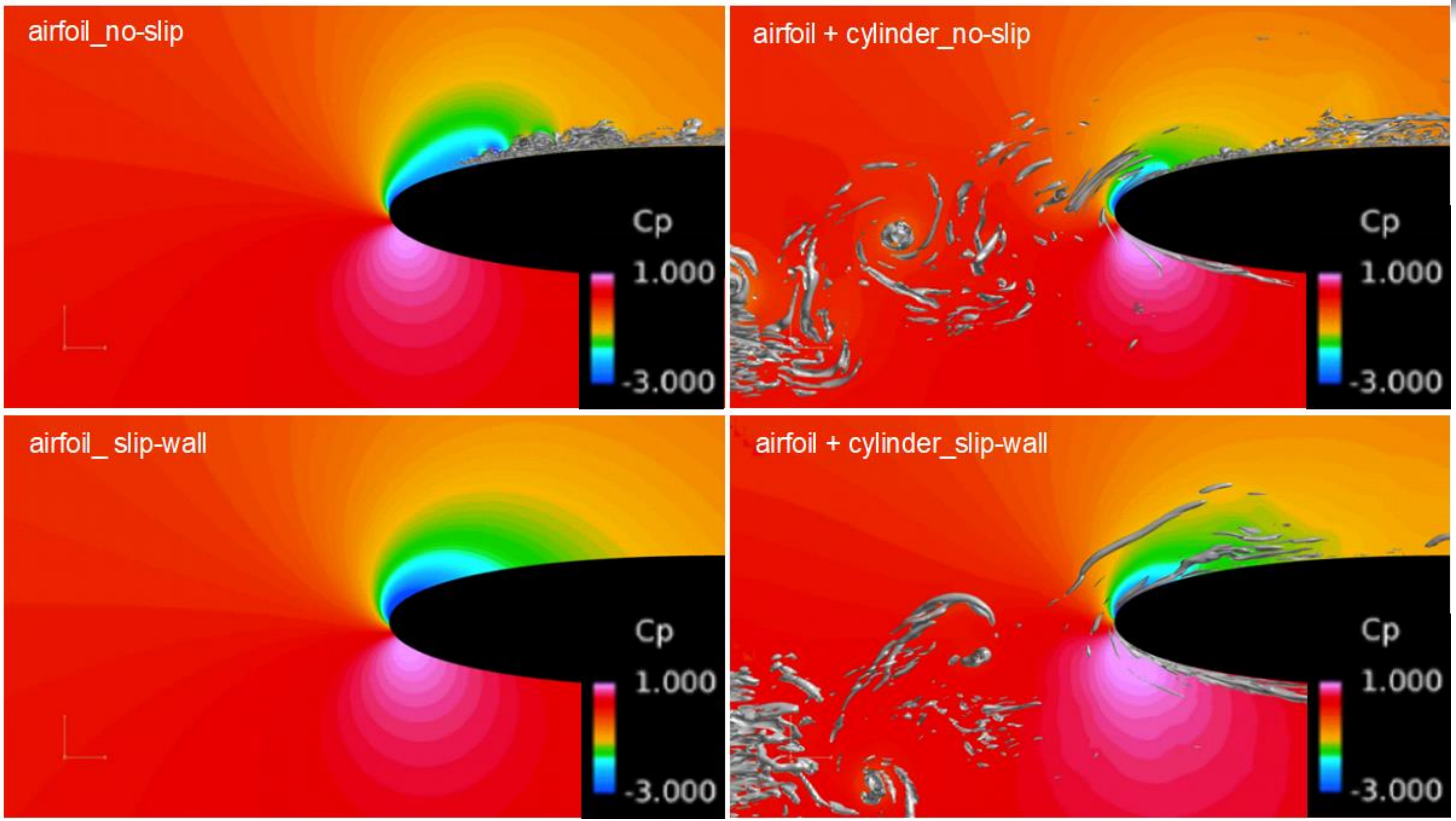


Non-dimensional frequency of 5

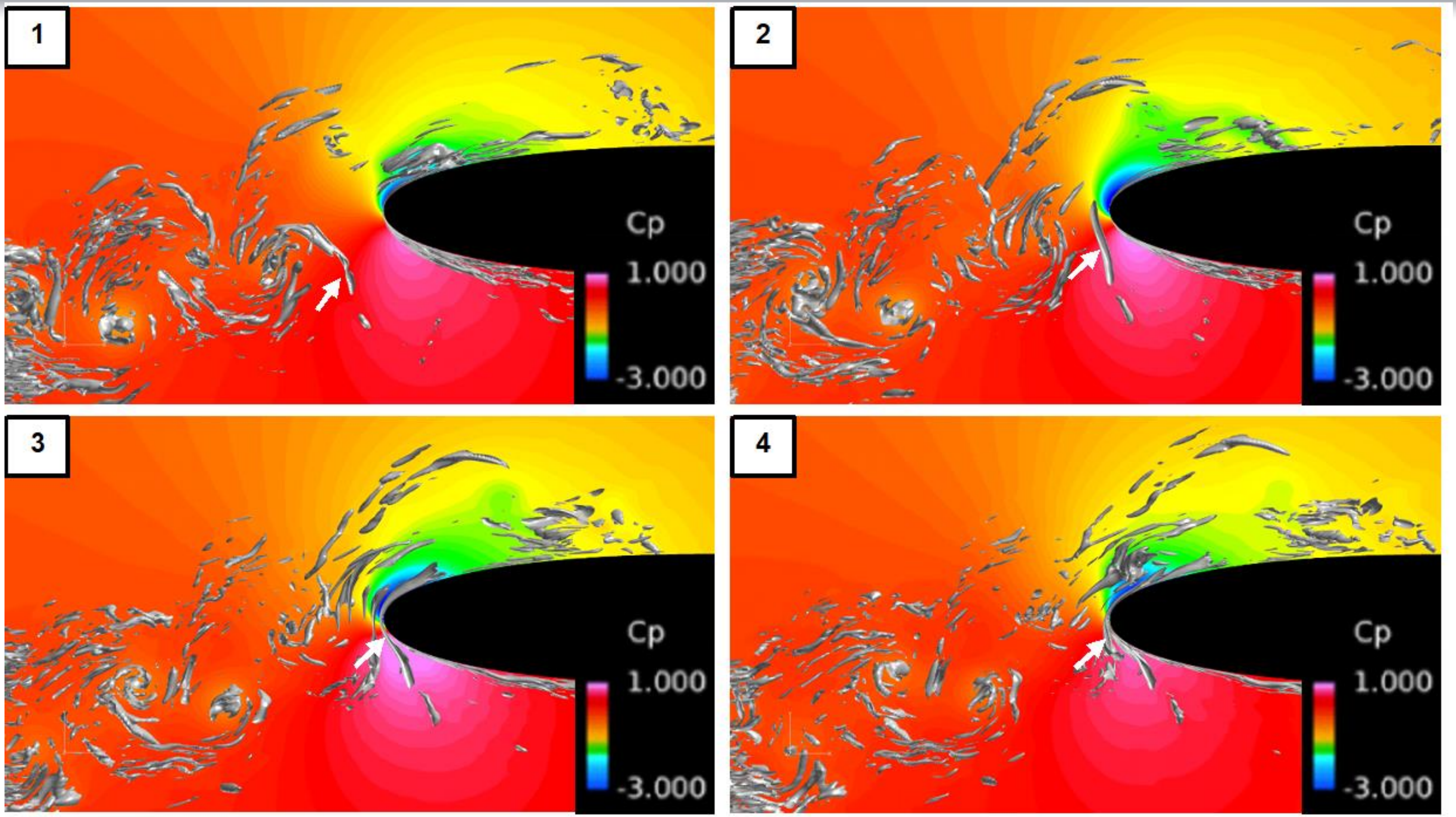
Non-dimensional frequency of 10

Without Cylinder | **With Cylinder** | **With Cylinder: slip wall on airfoil surface**

Effects of Cylinder and/or Self Turbulence of Airfoil



Vortices Stretched on Lifting Surface



Consortium Projects to Promote Industrial Applications (to be presented in site)

Conclusions and Perspectives

Concluding Remarks

CISS
Center for Research on Innovative Simulation Software

- **Empowered by the latest HPC technologies, we are now able to predict turbulence in actual industrial flows.**
- **HPC simulation will also contribute to progress of basic research.**
- **We can extend our design capabilities by referencing reliable data sets generated by highly-accurate simulations.**
- **Continue to make progress in simulation technology, which is needed to advance design methods, empowered by AI.**

An overview and Perspective of Simulation on High-performance Computing

②
Orthogonal mesh

①
Massively Parallel Computation

③
POD･DMD･
Surrogate model

Automated preprocessing → **Wall-resolving LES** → **Intellectualized post-processing**

④
Intellectualized flow solver by machine learning

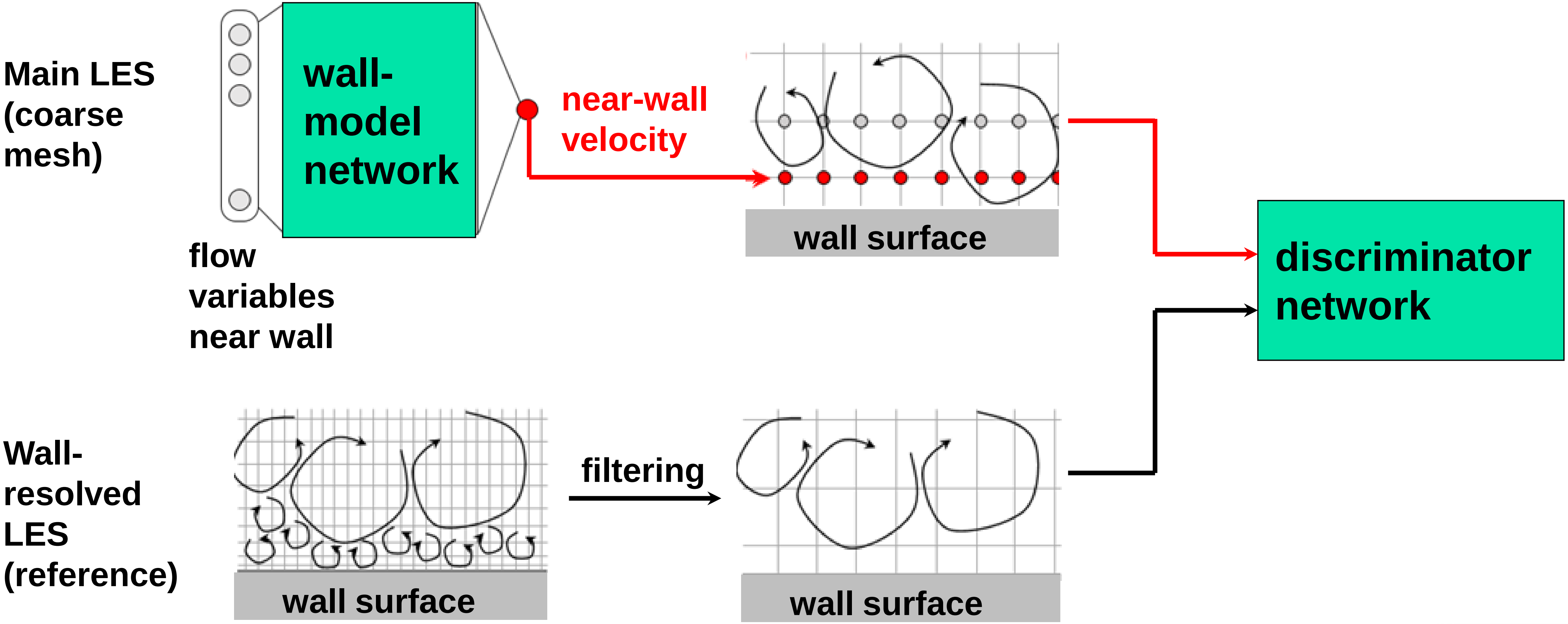
Intellectualized flow solver by machine learning

- To drastically reduce computational costs

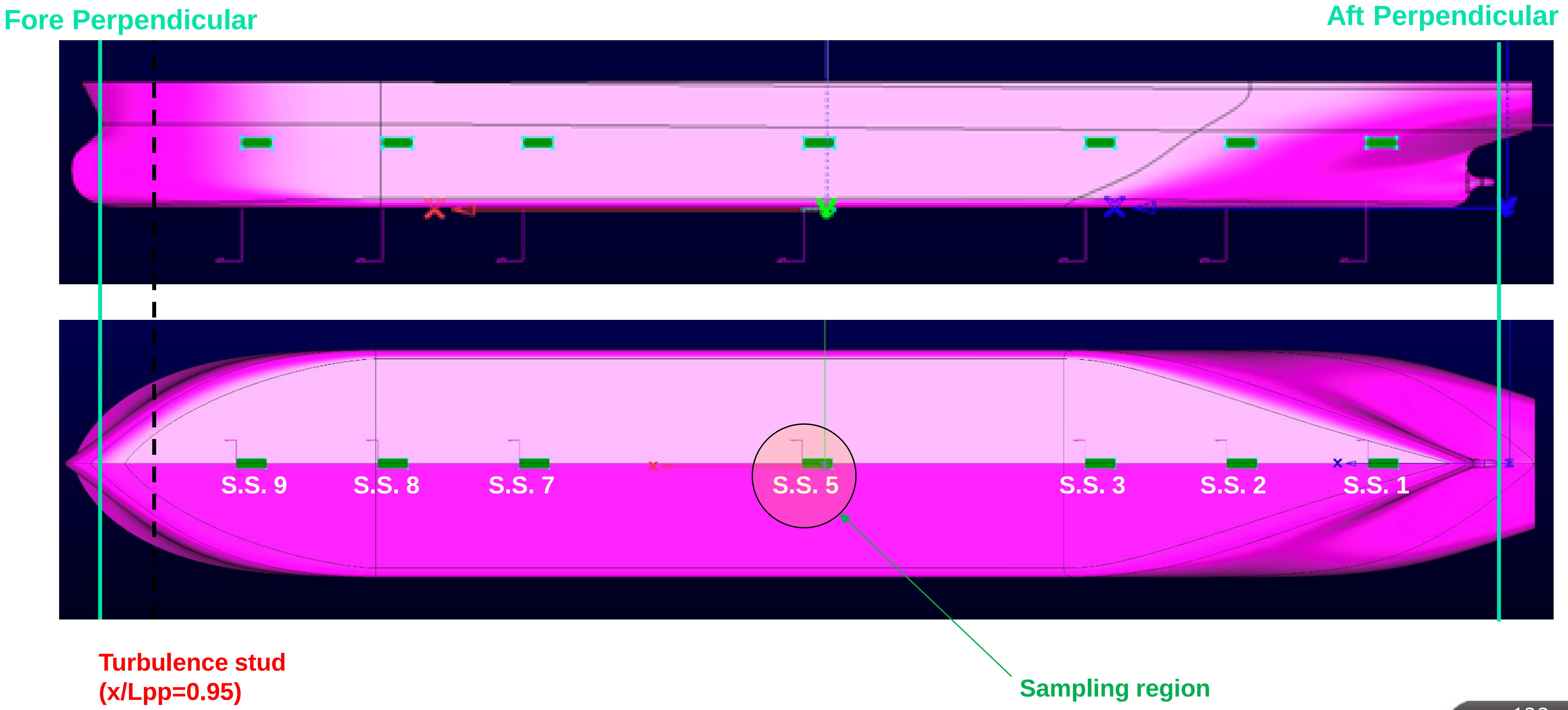
- To development Innovative algorithm that is not limited by memory size or memory throughput

Machine-learned Wall Model for LES

- Achieve wall-resolving accuracy by coarse computational mesh



Machine Learning of Model Parameters



Machine Learning of Model Parameters (cont'd)

$y^+=100$ $y^+=200$ $y^+=300$

u[0.3:1.3]

Modelled flow field

Referenced flow field

v[0.3:1.3]

Modelled flow field

Referenced flow field

w[0.3:1.3]

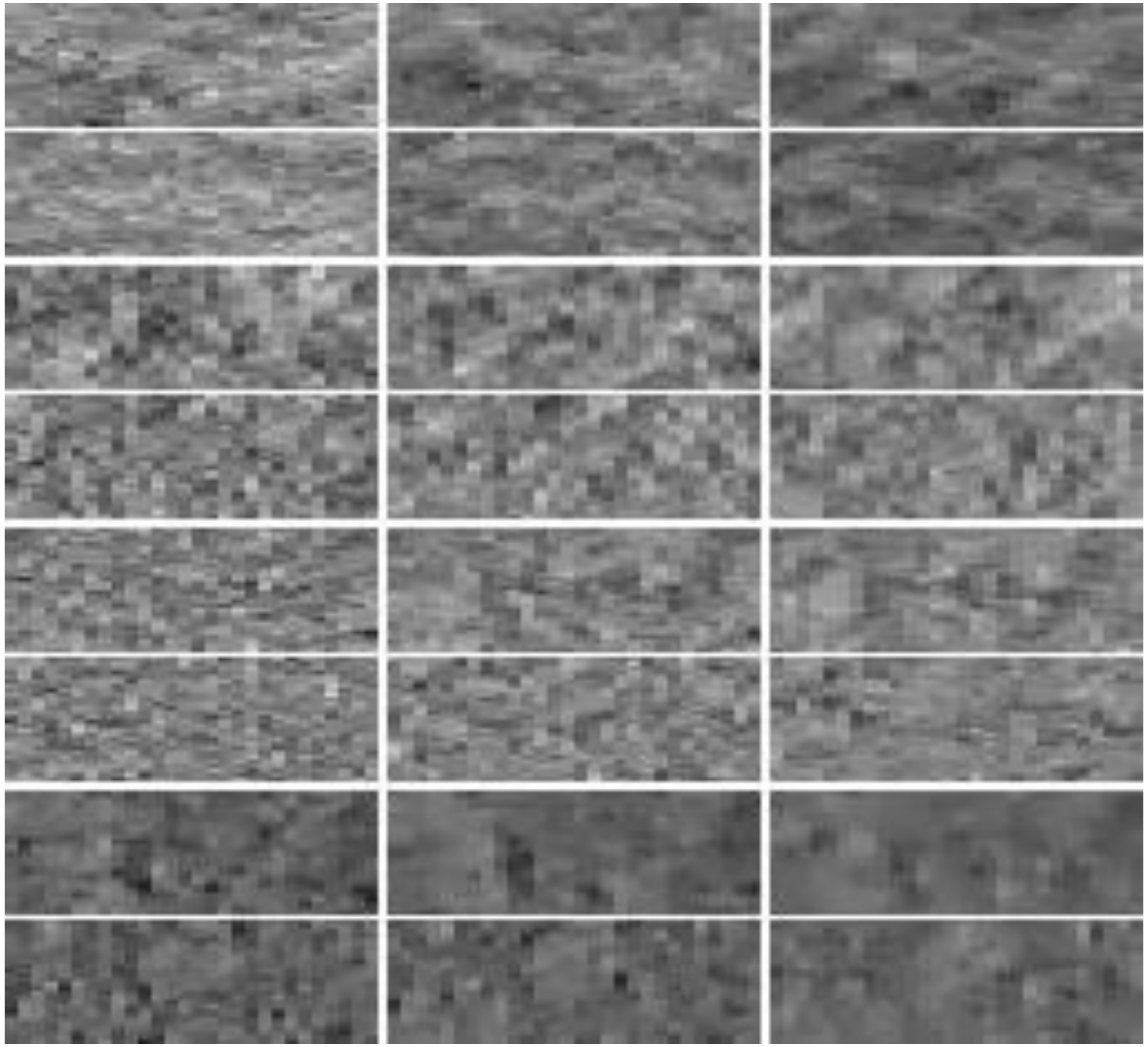
Modelled flow field

Referenced flow field

p[0.3:1.3]

Modelled flow field

Referenced flow field



Acknowledgment

- MEXT for sponsoring this project and providing the computational resources on K computer and supercomputer Fugaku

- Fujitsu Limited for their technical supports with code optimization

- Special Thanks for Drs. Isobe and Kato from NEC for their support for porting and optimizing FFB and FFX on NEC Aurora-TSUBASA

- Many industrial partners for cooperation with this project, in particular,
  - Hitachi Industrial Products, Co., Ltd., Toyota Motor Corporation, Honda Motor Co., Ltd., SUZUKI MOTOR CORPORATION, EBARA CORPORATION, Shipbuilding Research Centre of Japan.