Future trends of applications of CFD to industrial design

Fully-resolved LES (Large Eddy Simulation)

- Resolve such eddies that are responsible for production of turbulence in TBL
  - $\lambda_x^+=300$, $\lambda_y^+= 30$, $\lambda_z^+ =150$
- Only model eddies in dissipation scale, thus most reliable
- Provide as accurate solution as DNS as long as flow of interest is properly resolved, with approximately a 1/100 cost of DNS

How small are the active eddies in turbulent boundary layer?

- Flat-plate turbulent boundary layer at $l = 1m$

Re_l	δ	d	d/δ
1×10^5	37 mm	5.1 mm	0.140
1×10^6	25 mm	600 μm	0.026
1×10^7	15 mm	77 μm	0.005

δ: Thickness of boundary layer
d: Scale of active eddies in TBL

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Computer resources required for fully-resolved LES

- Automobile aerodynamics
  - Free-stream velocity : 30 m/s
  - Length scale : L=2 m
  - Reynolds number : Re_x=4 million
  - Friction velocity : 1.2 m/s
  - Viscous scale: 12.5 μm
  - Diameter of active smallest vortices : 0.4 mm
  - Minimum grid size= : 0.1 mm (100 μm)
  - Surface grids per 1 m^2 : 100 million
  - Number of grids in total : 40 billion
  - Computational resources : 40,000-200,000 cores

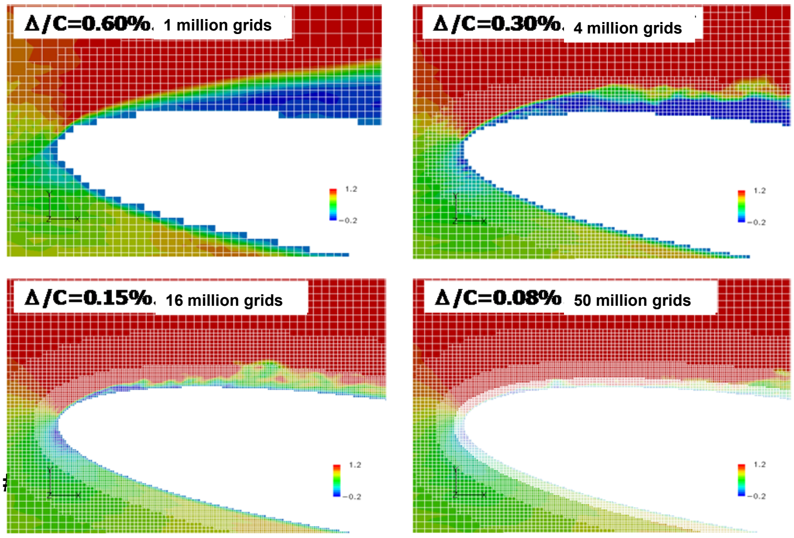
Engineering Applications of Fully-resolved LES

■ **Applications of LES expected in 2015**

products	specifications	R_e	# of TBLs	Total # of grids
automobile	L=2 m, U=28 m/s (100 km/h)	4.0×10^6	20	40 billion
model ship	L= 5m (1/50 scale model), U=1.0 m/s	4.6×10^6	1.2	20 billion
model pump	D_2=300 mm, 1500 rpm, L=0.15 m, U=24 m/s	3.6×10^6	12	4000 billion
wind turbine	D_2=40 m, L=0.4 m, U=64 m/s	2.5×10^6	3	40 billion
axial-flow fan	D_2=600 mm, 1800 rpm, L=0.2 m, U=56 m/s	7.5×10^5	12	9 billion
propeller fan	D_2=500 mm, 600 rpm, L=0.2 m, U=16 m/s	2.0×10^5	3	100 million
small cooling fan	D_2=80 mm, 3400 rpm, L=0.02 m, U=14 m/s	1.9×10^4	7	1 million

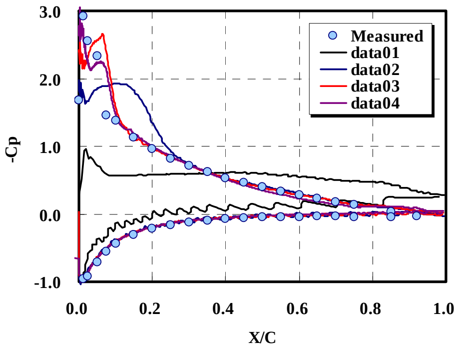
Development and Validations of Flow and Acoustical Solvers

Benchmark tests for airfoil flow

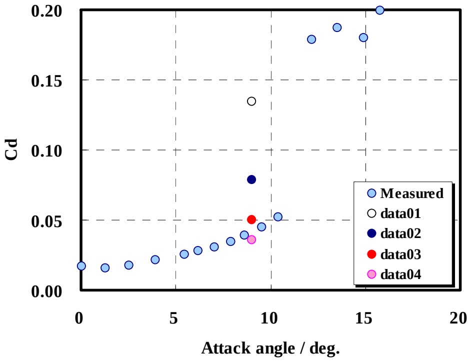


NACA0012 at angle of attack, 9 degrees, Reynolds number of 200,000

Benchmark tests for airfoil flow



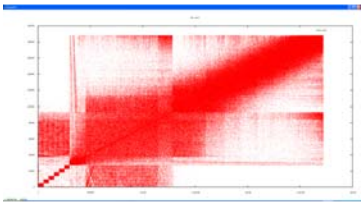
Surface pressure distribution

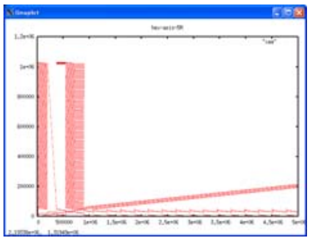


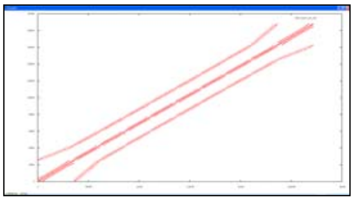
Drag coefficient

Code tunings-1/3

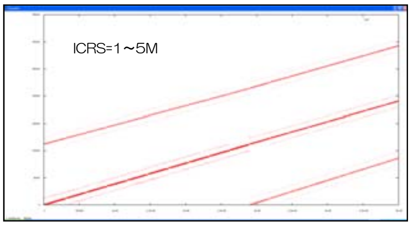
- Data reordering for minimizing occurrence of L1, and L2 cache miss







Tetrahedral elements



Hexahedral elements

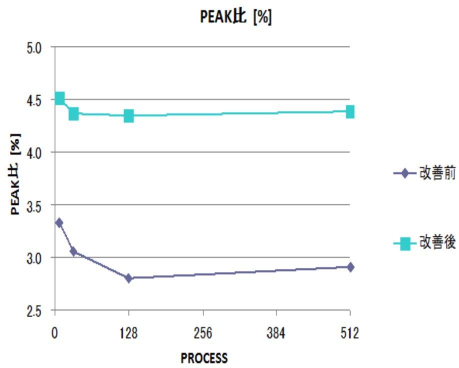
Code tunings-2/3

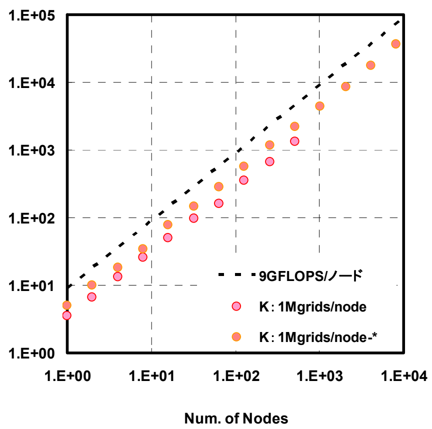
- Sustained performance of the hot kernel

	Hexahedral element	Tetrahedral element
Original (1core)	5.9%	2.4%
Full unroll (1core)	10.8%	4.2%
Full unroll (8core)	5.4%	3.0%
Full unroll ＋ Reordering (1core)	10.2%	10.2%
Full unroll ＋ Reordering (8core)	8.1%	7.7%

Code tunings-3/3

■ Overall Performance and speed-ups





Ratio of sustained to peak performance

Parallel computing performance

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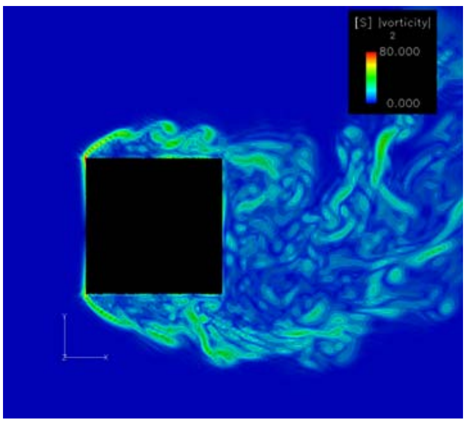
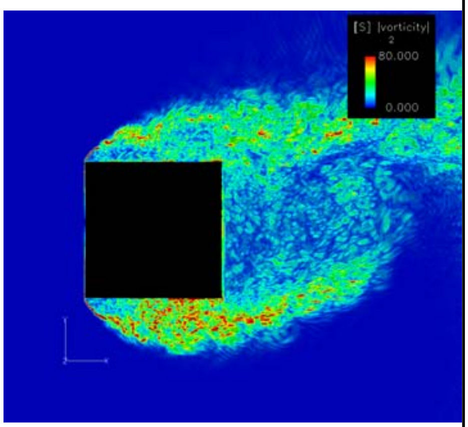
Sensitivity Studies on Grid Resolutions

■ Comparisons of Instantaneous Streamwise Velocity



22 million grid



55 million grid

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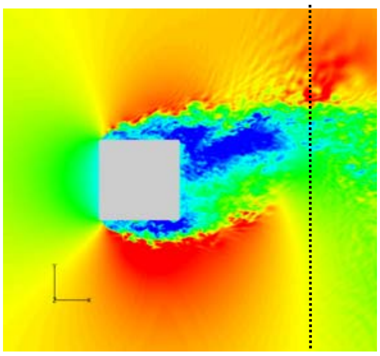
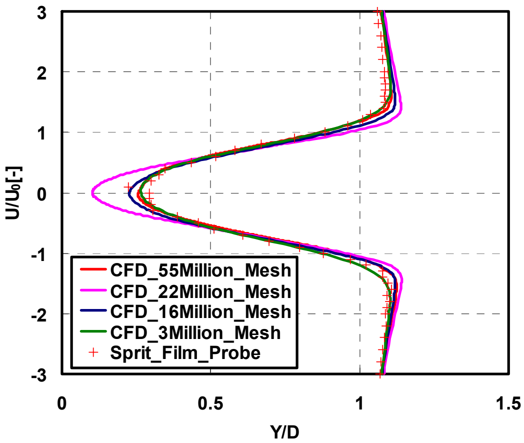
Validation Studies-1/2

■ Comparisons of Time-averaged Wake Profile



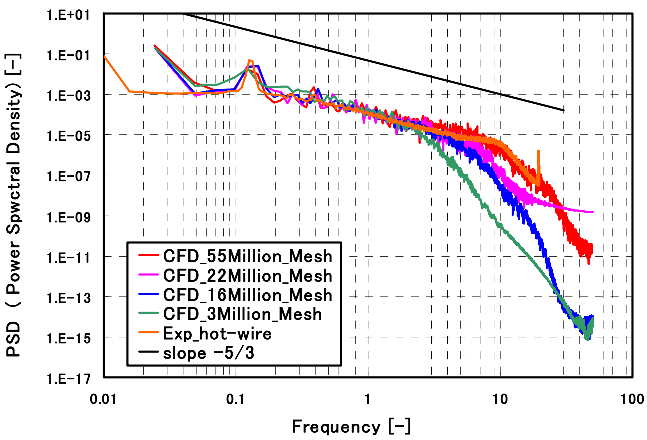
Instantaneous flow



Near wake at x=1.5D

Validation Studies-2/2

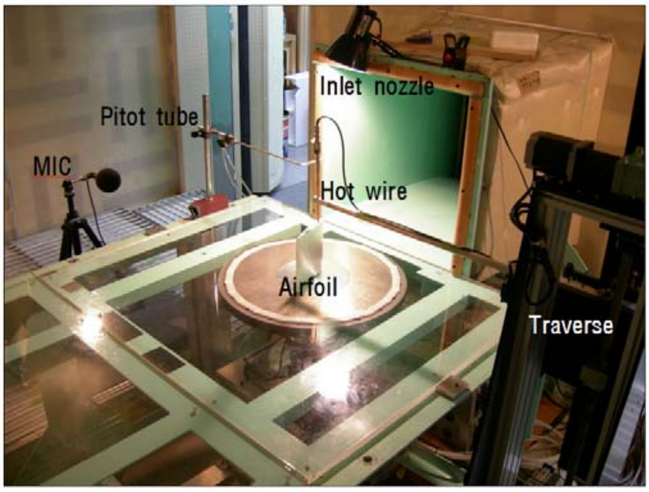
■ Comparisons of PSD of Streamwise Velocity



Fully developed wake (x=3D)

Experimental Setup

- Measured: drag & lift, surface pressure, velocity profile, sound



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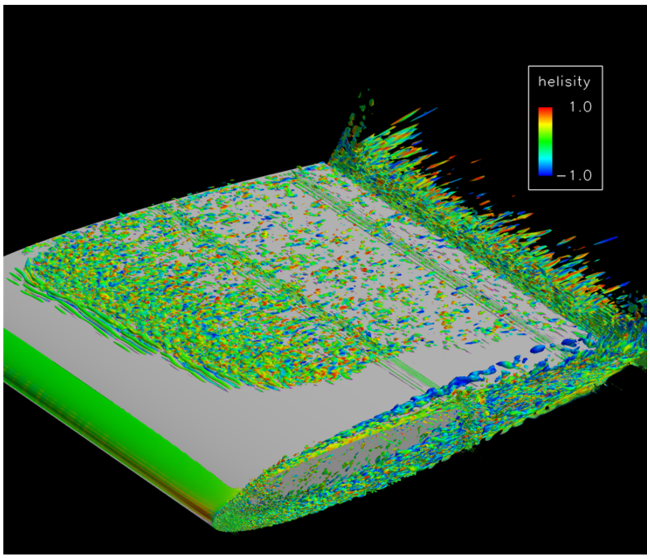
Instantaneous Flow



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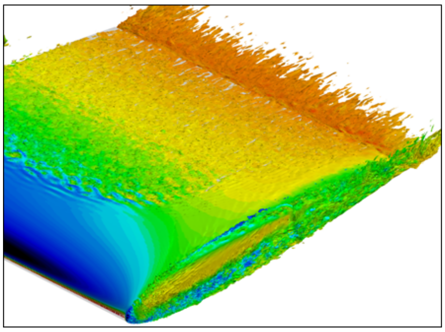
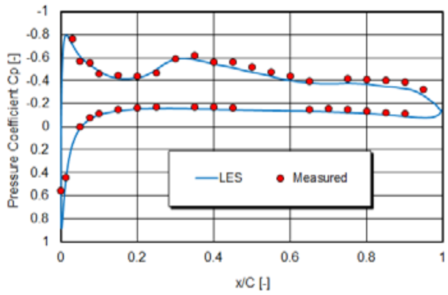
Validation Studies



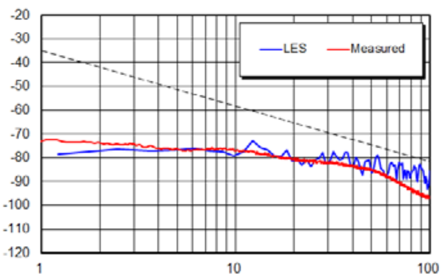


Instantaneous flow structures

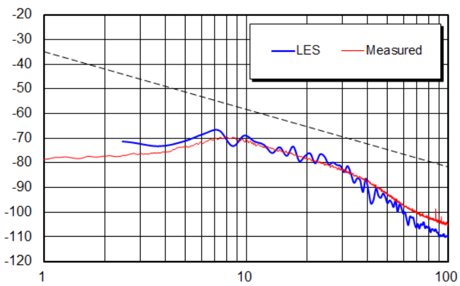
Time-average pressure distribution near tip(z/c=-0.1)

Validation Studies (continued)

■ PSD of static pressure fluctuations at tip



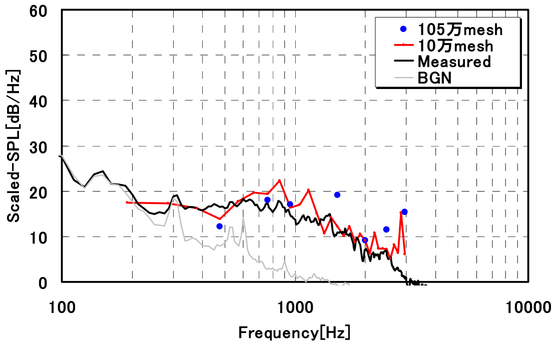
x/C=0.1



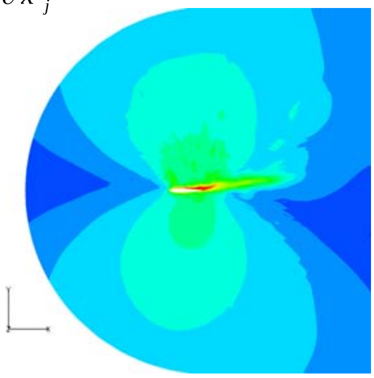
x/C=0.6

Predicted far-field sound

- **Acoustical field computed by Lighthill equation:** $\frac{\partial^2 \rho}{\partial t^2} - a^2 \frac{\partial^2 \rho}{\partial x_i^2} = \frac{\partial^2}{\partial x_i \partial x_j} T_{ij}$

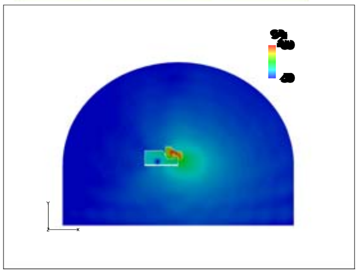


Comparison of sound pressure level

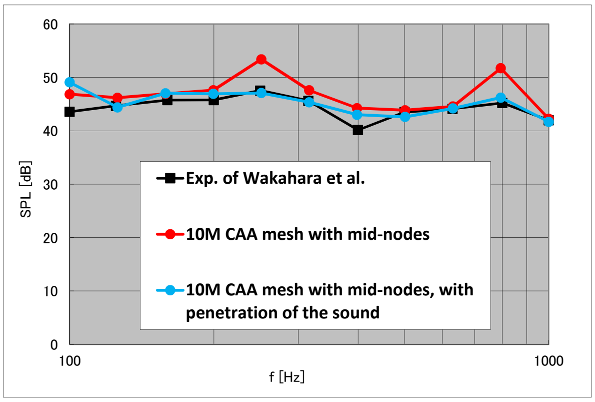


Sound field at St=5.7 (760 Hz)

Benchmark test for HVAC sound



Sound field at 760 Hz



Comparison of sound pressure level

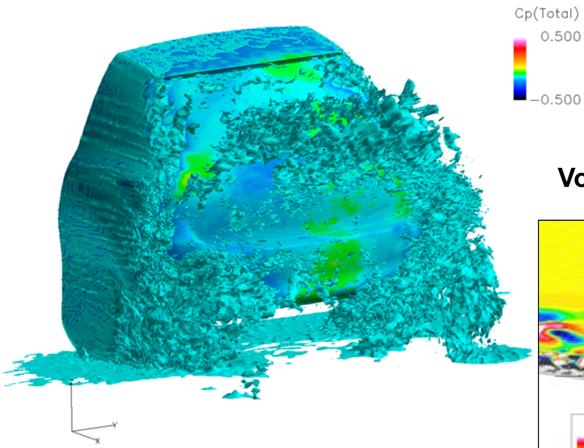
Application Examples

Drag Reduction of Passenger Car by Controlling Vortical Structure behind Car

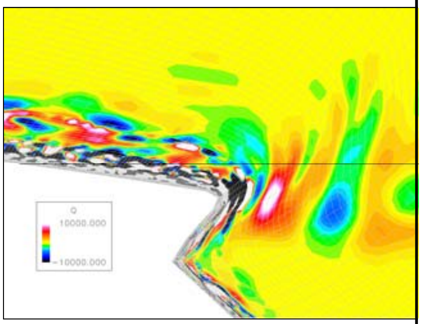
(Reynolds number=1.0×10^6, # of grids = 2 billion)

Collaborator: Toyota Motor Corporation

How automatic grid refiner works?



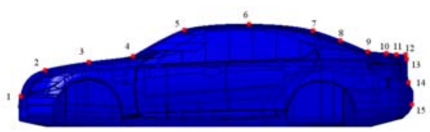
Vortices in viscous sub-layer

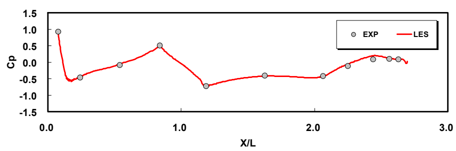


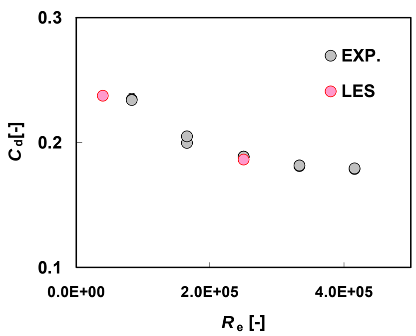
Overall flow structures

Comparison with Wind-tunnel Data

■ Accuracy Validations



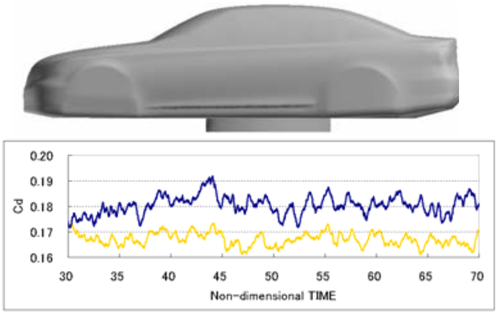




Static Pressure Distribution around Car Body

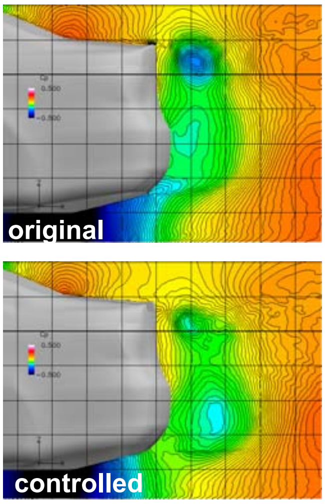
Reynolds Number Dependency of Drag

Drag Reduction by Vortex Control



	Time average	RMS
Original shape	0.181	0.0041
Controlled shape	0.168 (-7%)	0.0031

Predicted drag coefficients



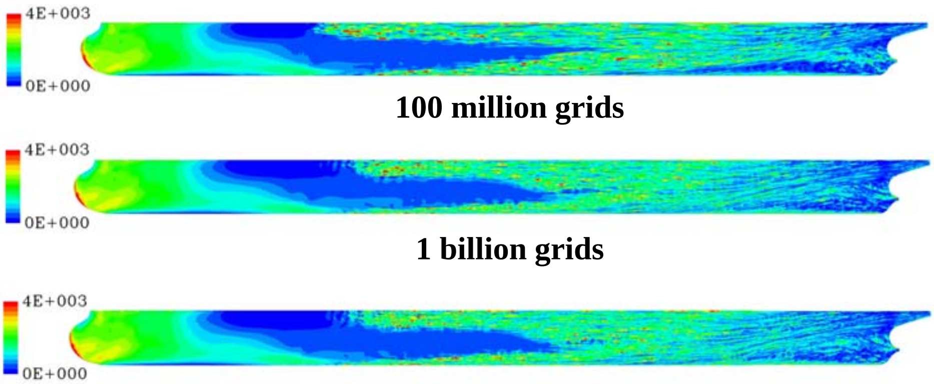
Wake structures

Drag prediction for model ship

**(Reynolds number=5 million,
# of grids = 8 billion)**

Collaborator: SREC

Grid-convergence Studies

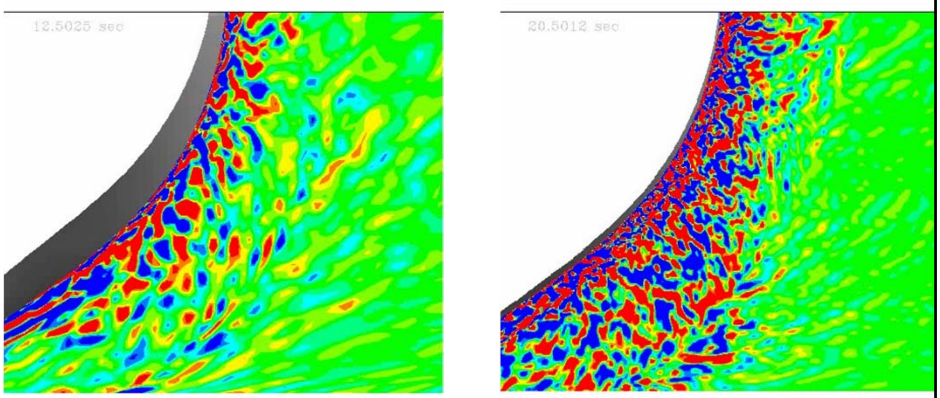


100 million grids

1 billion grids

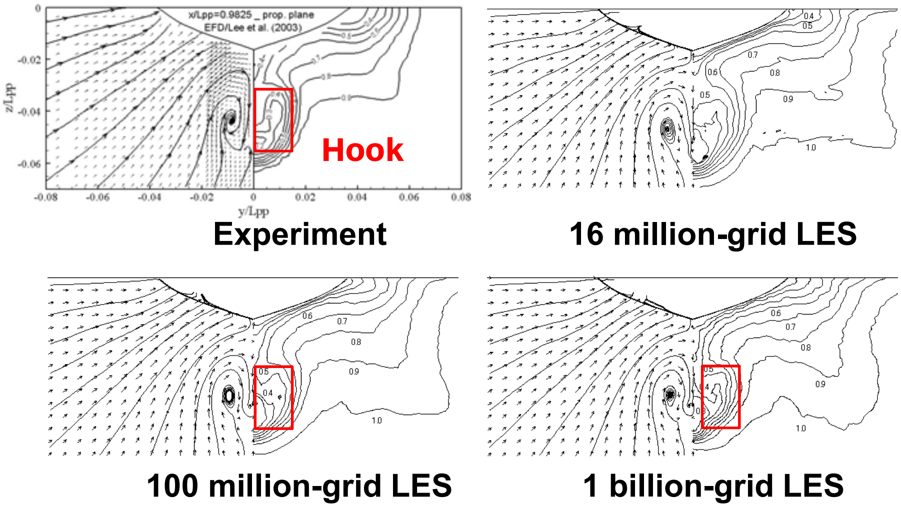
8 billion grids

Vortex Behaviors



16 million grid | **Refined 8 billion grid**

Comparisons of Velocity Contours on Propeller Plane



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