

Building-Cube Methodによる流体解析

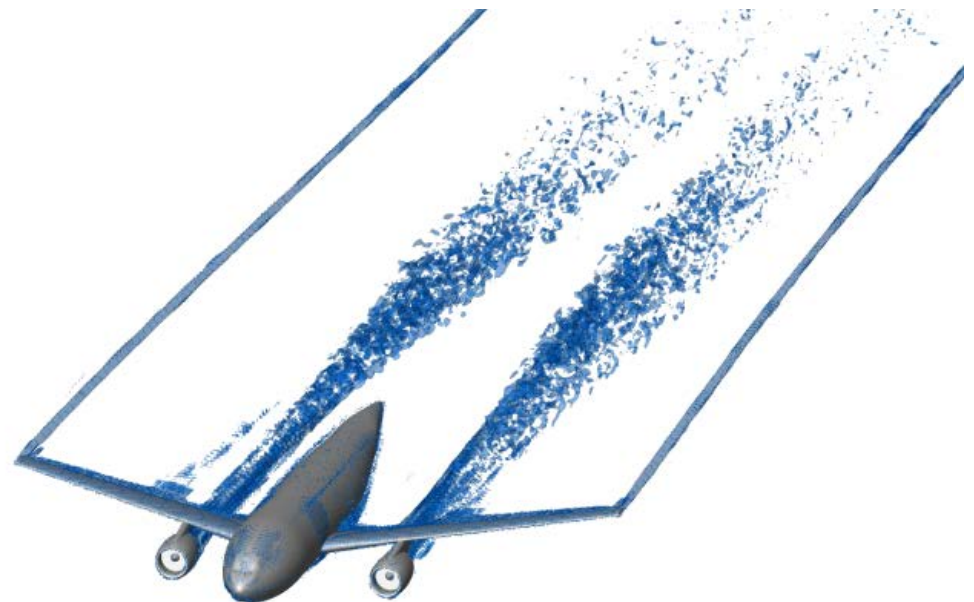
三坂 孝志(東北大学)

地球流体データ解析・数値計算ワークショップ

2015年3月10日

目次

- 自己紹介
- 研究の背景(航空気象, データ同化)
- 航空CFDとBuilding Cube Method (BCM)
- BCM利用例の紹介
- 高レイノルズ数流れへの対応
- まとめ



自己紹介

東北大学

- 修士(航空宇宙工学専攻):
 - DBDプラズマシミュレーション(プラズマテレビ, オゾン殺菌)
- 博士(システム情報科学専攻)
 - 晴天乱気流(フライトデータ, JAXAライダー)
 - 後方乱気流(ENRIライダー)
 - それらへのデータ同化法の適用

ドイツ航空宇宙センター大気物理研究所(DLR-IPA)

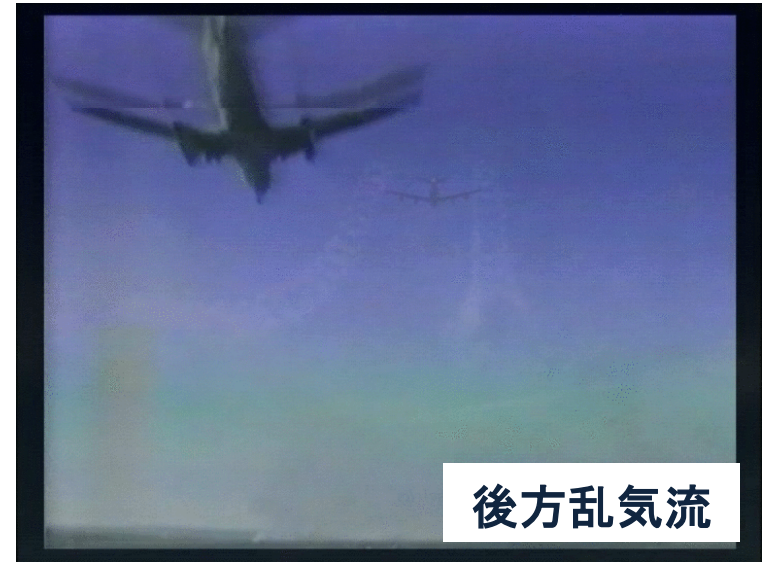
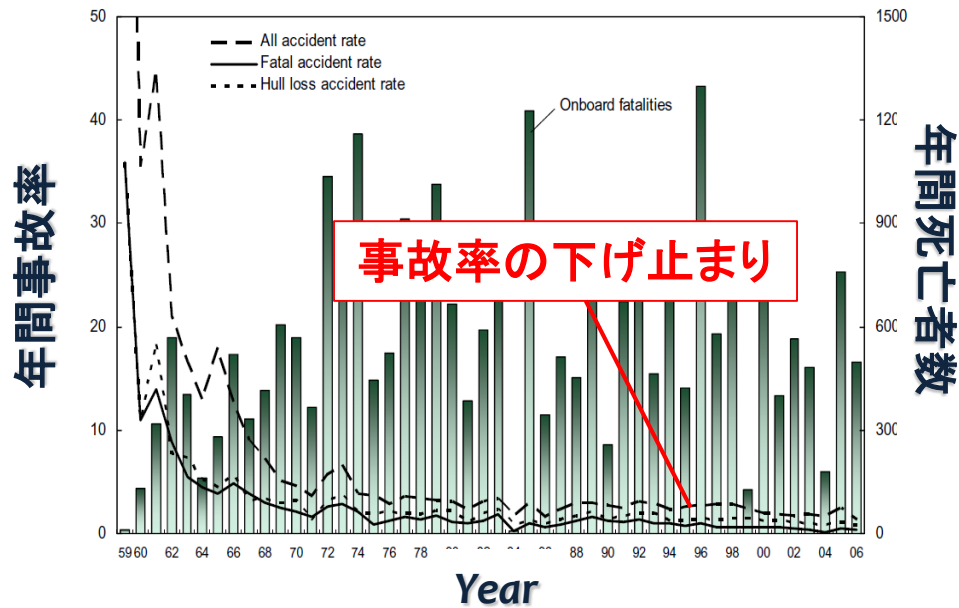
- ポスドク研究員
 - 後方乱気流の続き(主にLES)



(再び)東北大学

- 助教(学際科学フロンティア研究所&流体科学研究所 大林研究室)
 - 航空気象(少し)
 - Building-Cube Method(大規模計算向け直交格子CFDコード)
 - データ同化の応用(主に工学分野)

乱気流の運航安全への影響



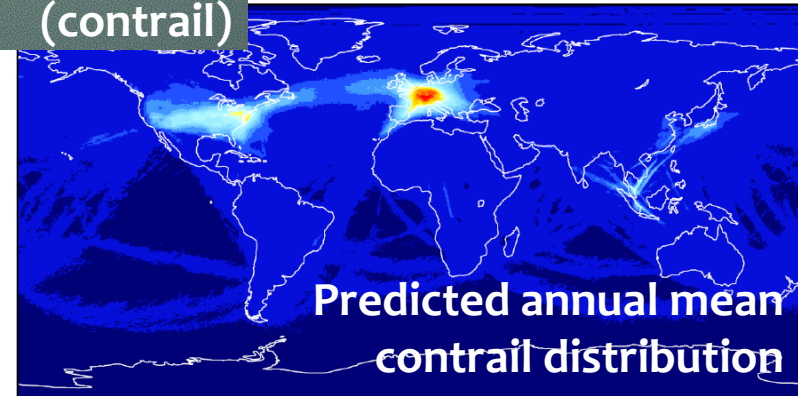
- ここ十数年の事故率の下げ止まりは、将来の事故数増加に繋がる可能性 (旅客数はこの先20年で2倍に増加と予想)
- 気象に関連した事故の割合が相対的に増加 (けがを伴う事故の約半数は乱気流関連)
- 流体现象としての乱気流に関する知見は驚くほど少ない (乱気流の揺れ: 1Hz → 200m程度の気流変動)

航空機の地球環境への影響



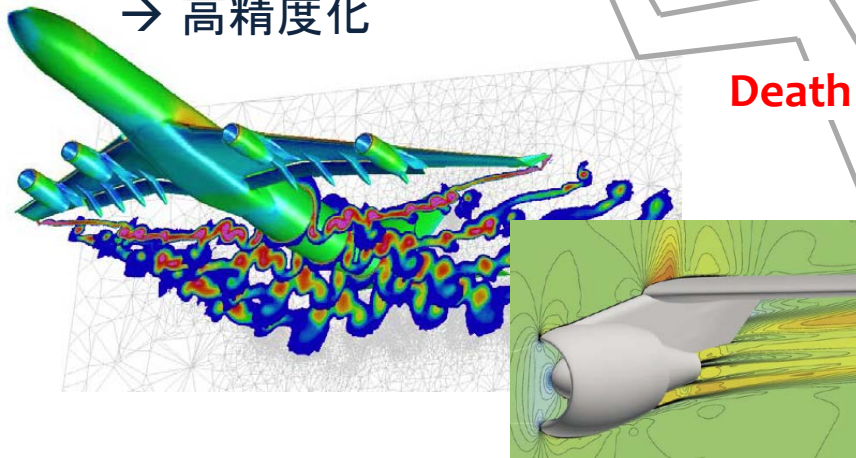
マイクロ・メソスケール 気象

→ 高解像度化



航空機の解析技術

→ 高精度化

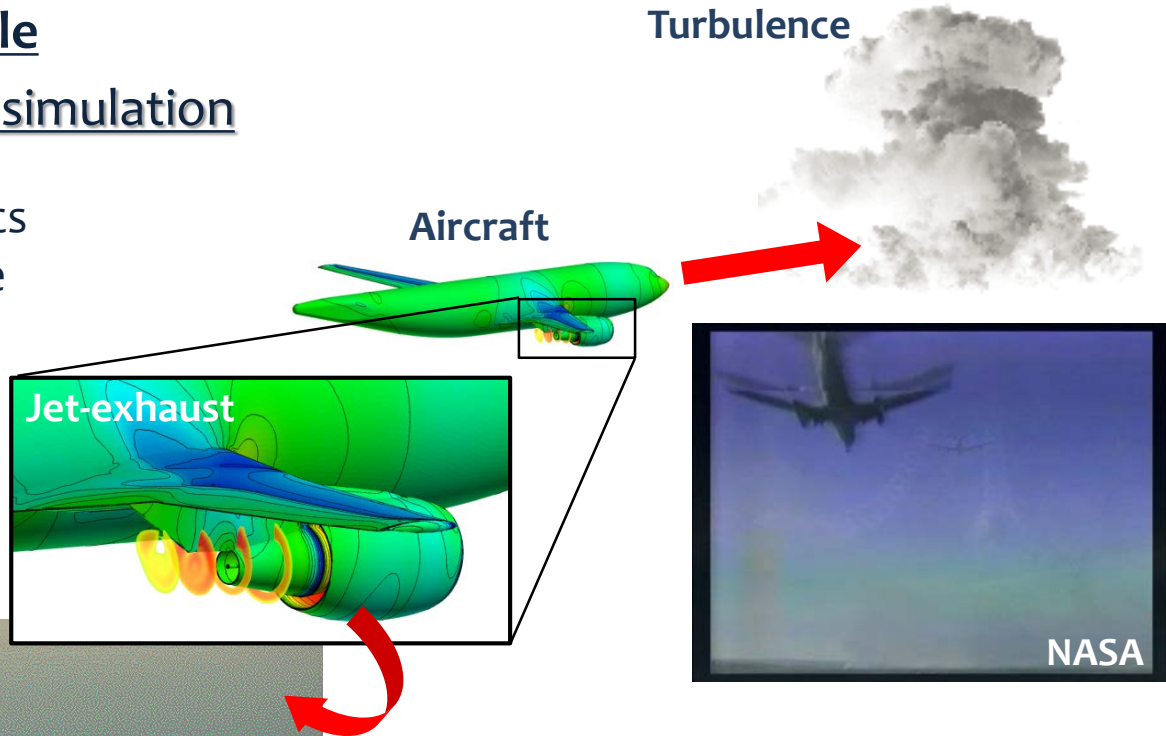


- 空間スケールの隔たり
(数m⇔数km)
- 研究コミュニティの違い

The gap of space-time scale

→ A large-scale computer simulation

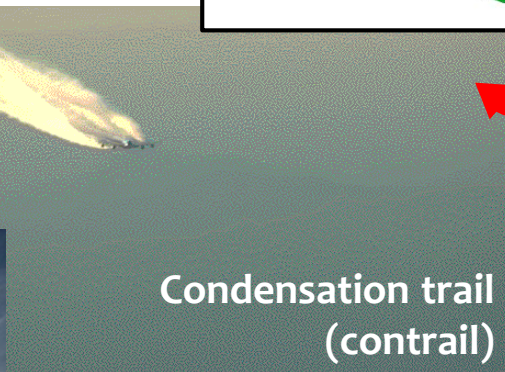
Multi-scale and multi-physics simulation for first principle contrail modeling



The gap of reality

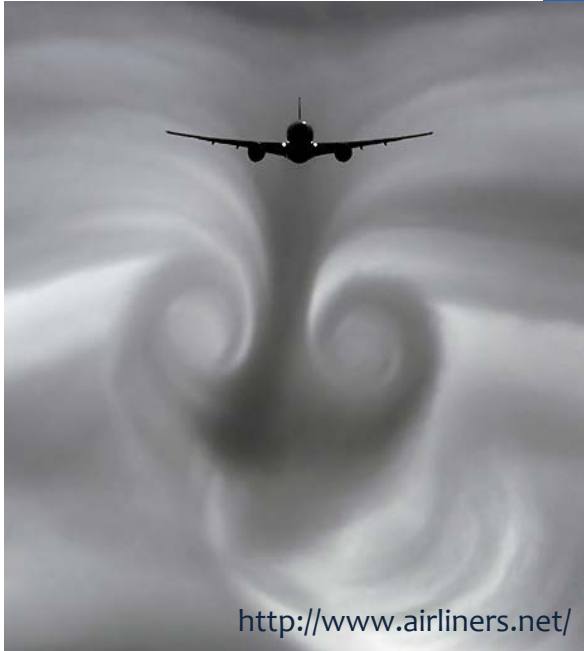
→ Data assimilation

Fitting a large-scale model with millions of parameters to a measurement data set

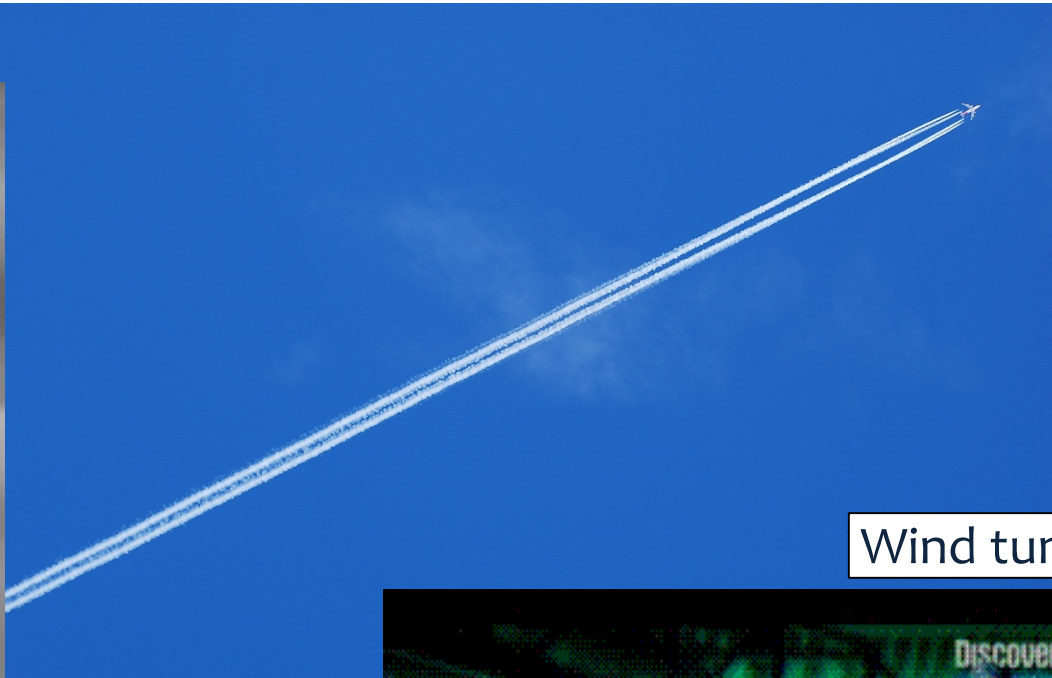


航空機の後流渦

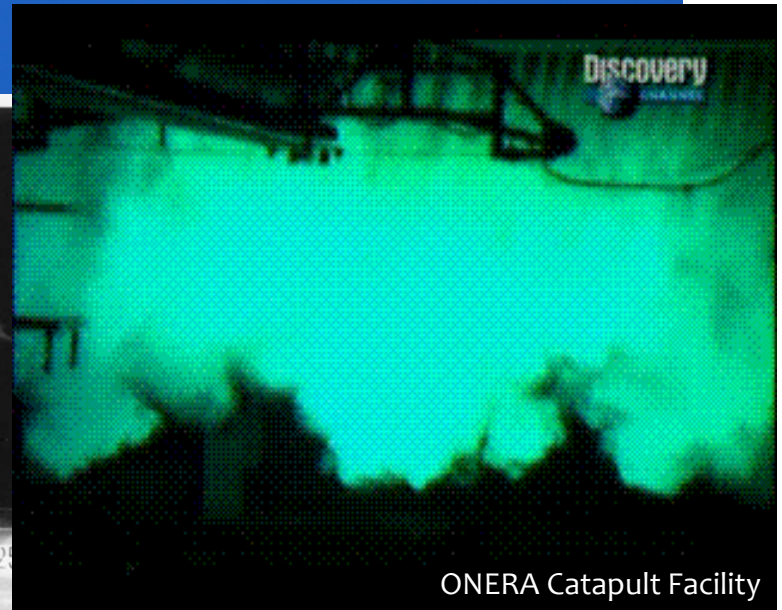
Real flight



<http://www.airliners.net/>



Wind tunnel

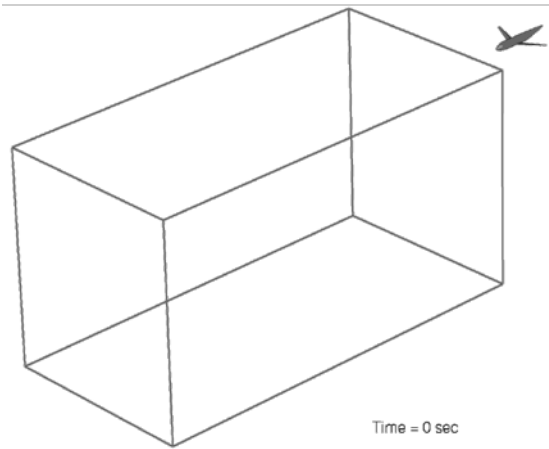


ONERA Catapult Facility



http://crgis.ndc.nasa.gov/historic/Vortex_Research_Facility

航空機後流と後流渦の形成

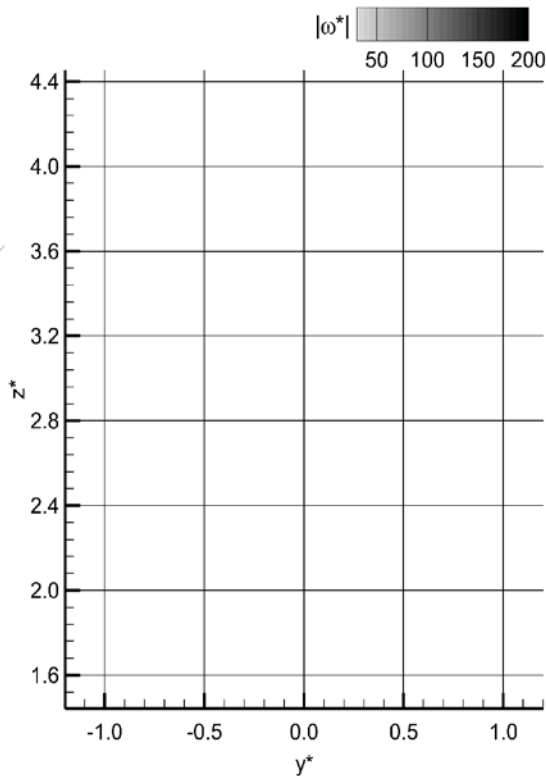


Wake initialization approach

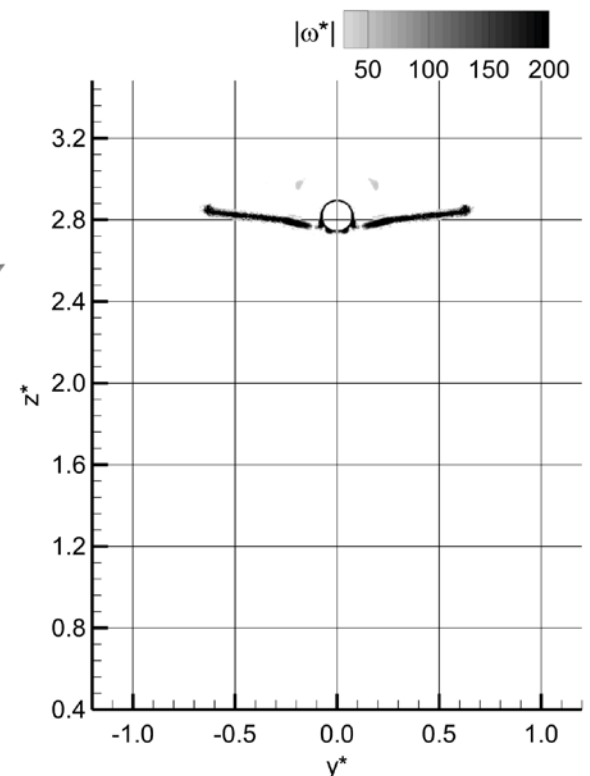
Realistic aircraft wake is generated by sweeping a high-fidelity RANS flow field through a computational domain



High-lift configuration



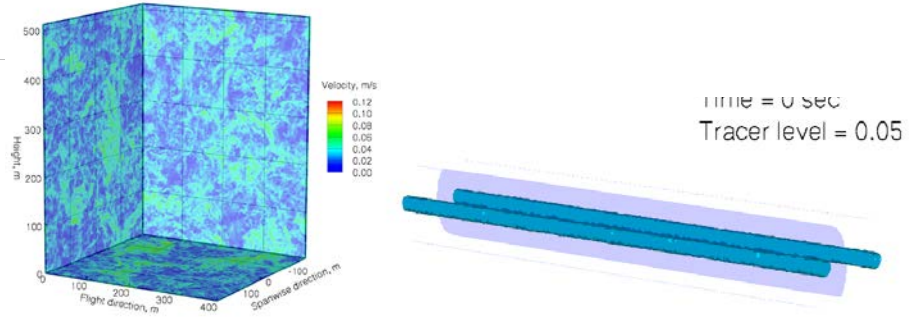
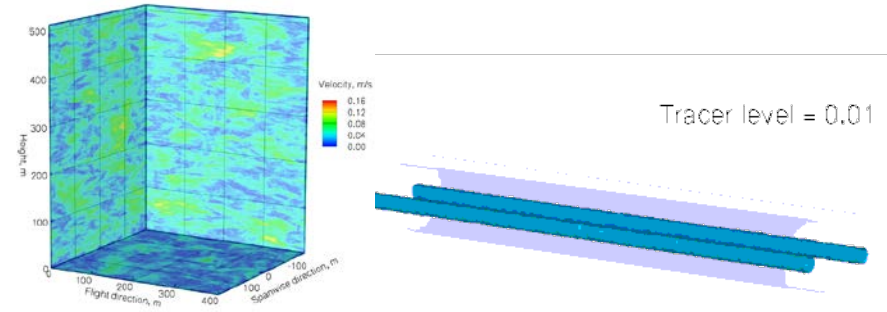
Wing-body configuration

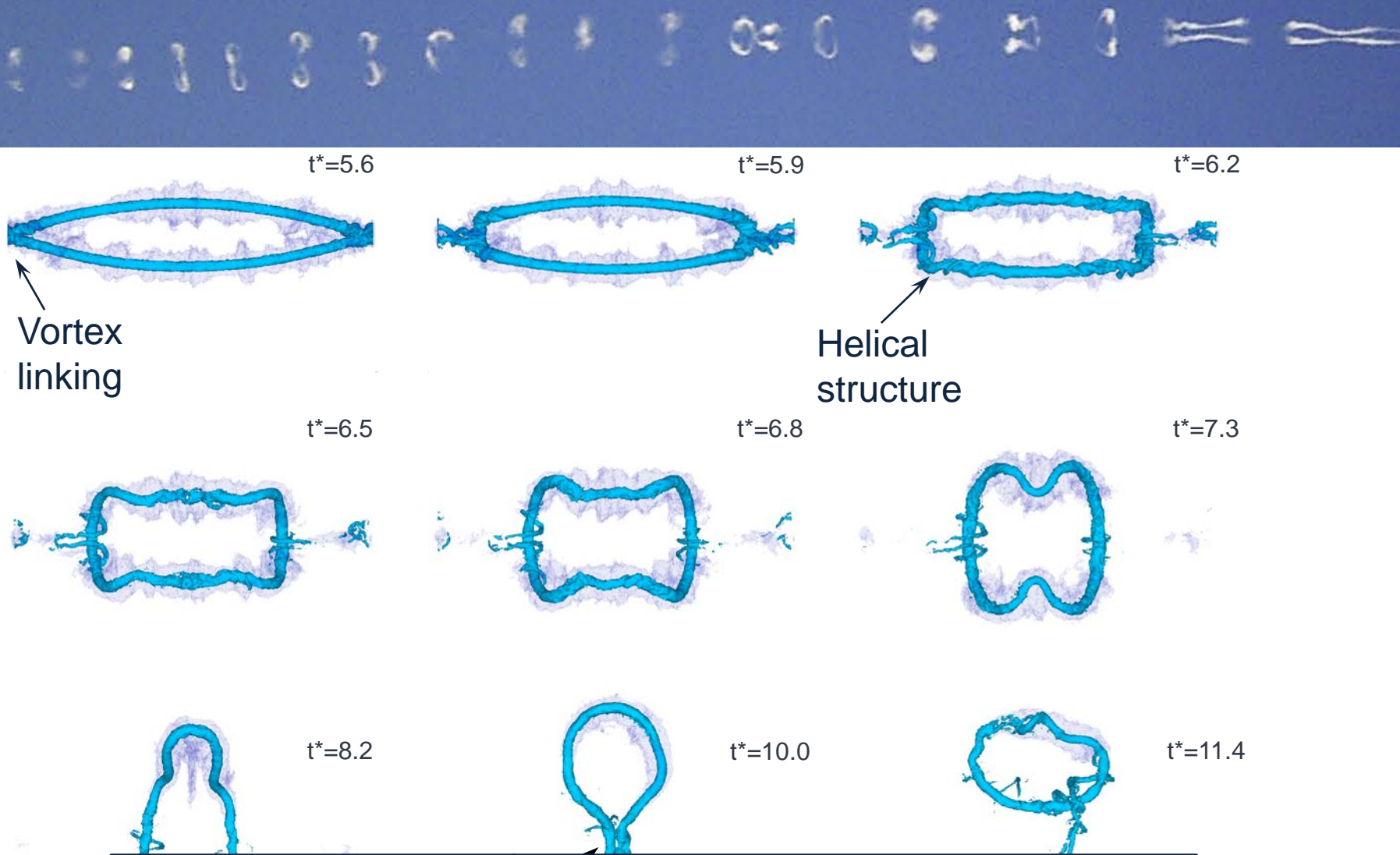


後流渦への大気乱流の影響

$\varepsilon^* = 0.01, N^* = 0.35$ (温度成層あり)

$\varepsilon^* = 0.01, N^* = 0.0$ (温度成層なし)

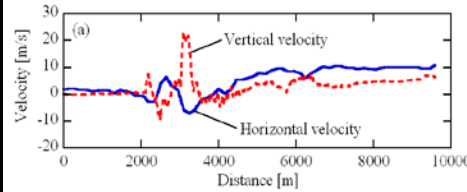
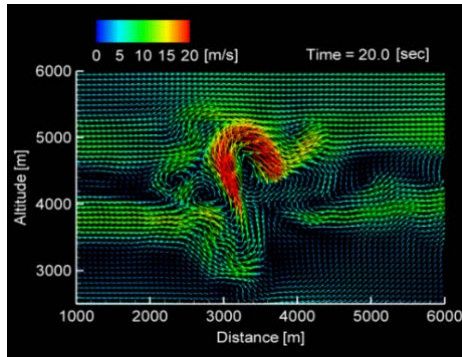




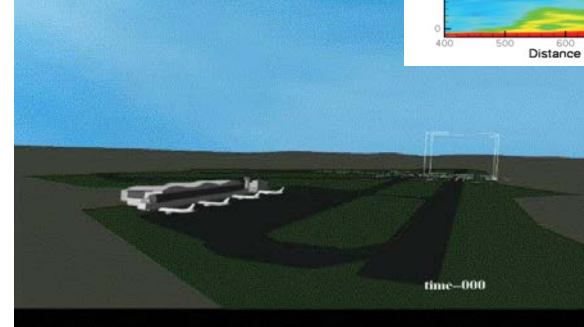
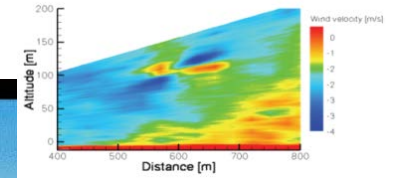
航空機から大気まで(大規模シミュレーション)
実環境を取り入れて解析(データ同化)

データ同化の航空気象への応用

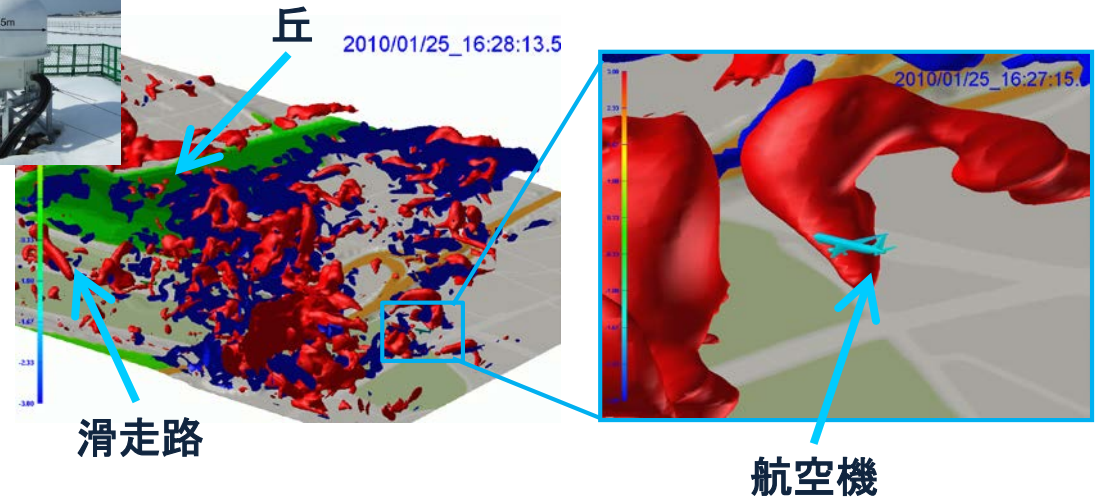
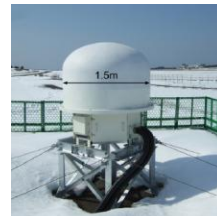
フライトデータ
→ 晴天乱気流



ライダーデータ
→ 後方乱気流

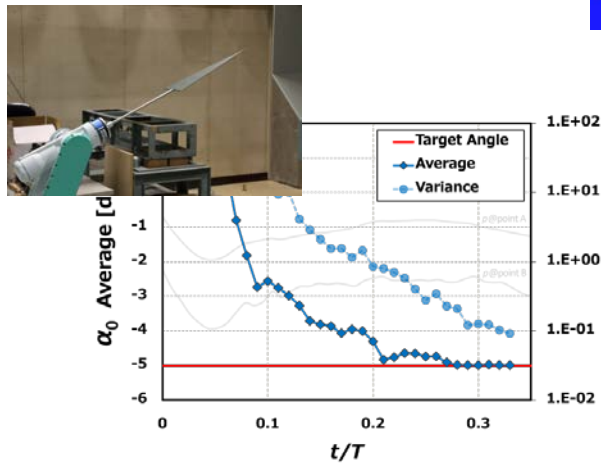


レーダーデータ
→ 低層風擾乱のリアルタイム予測

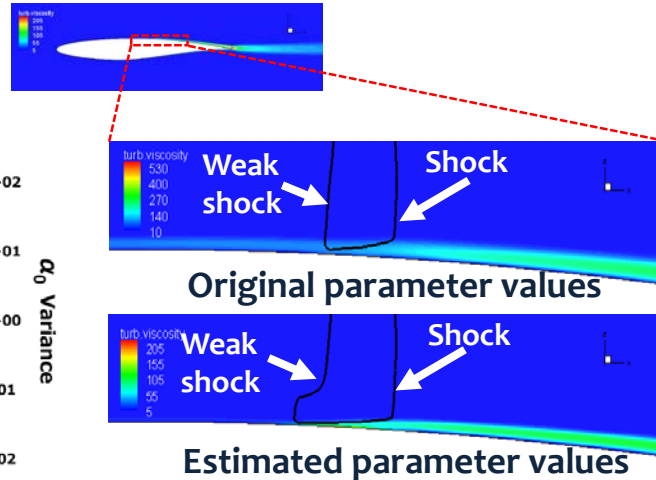


データ同化の流体力学問題への応用

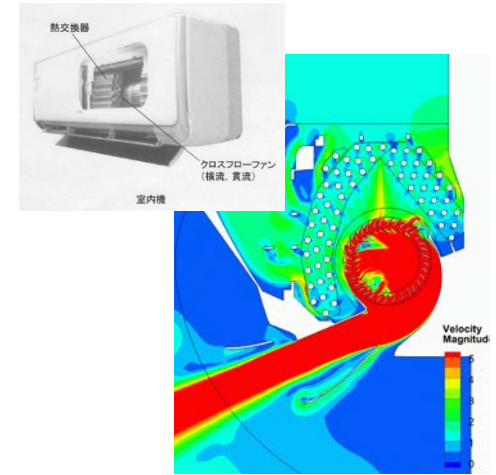
デルタ翼の動的風洞計測 融合シミュレーション



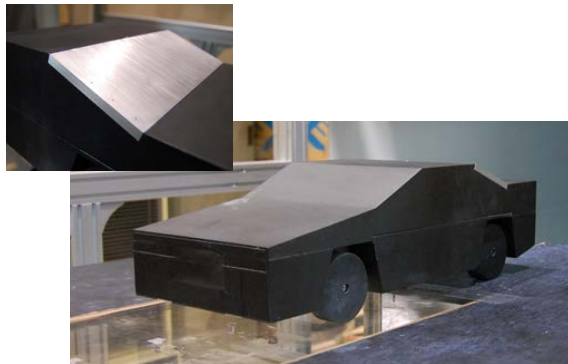
乱流モデルのパラメータ推定



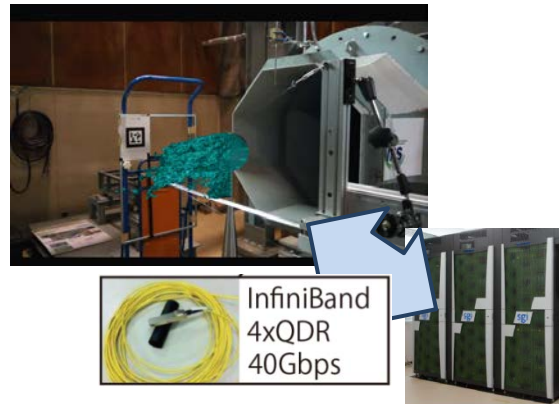
風速計測値を用いた多 孔質体の抵抗係数推定



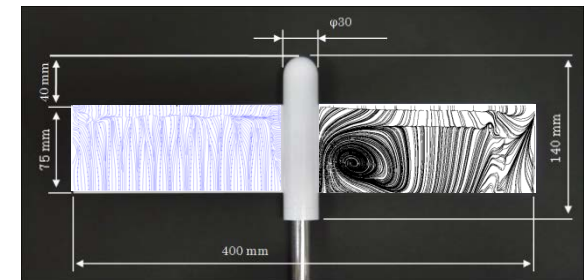
非定常圧力計測値を用いた 車両周りの流れ解析



スパコンを用いた 適応型計測

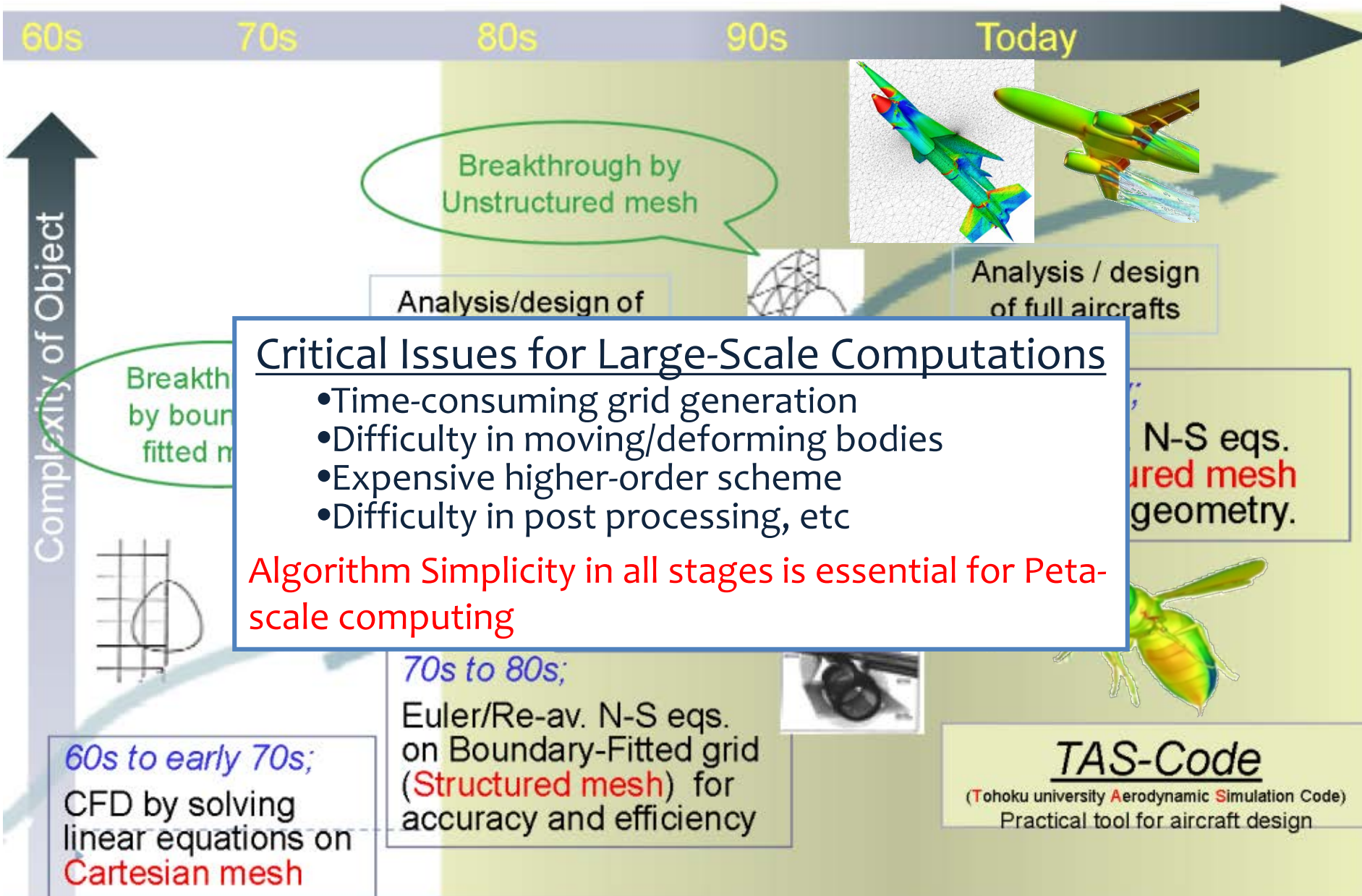


摩擦応力線を用いた 失速予測



大規模流体解析に向けた Building-Cube Methodの研究開発

航空分野の数値流体力学の変遷



60s

70s

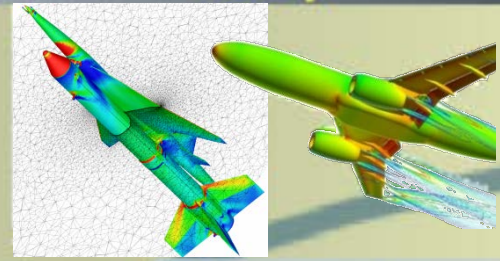
80s

90s

Today

Complexity of Object

Breakthrough by Unstructured mesh



Analysis/design of

Analysis / design of full aircrafts

Critical Issues for Large-Scale Computations

- Time-consuming grid generation
- Difficulty in moving/deforming bodies
- Expensive higher-order scheme
- Difficulty in post processing, etc

Algorithm Simplicity in all stages is essential for Petascale computing

N-S eqs. on unstructured mesh geometry.

60s to early 70s;
CFD by solving linear equations on Cartesian mesh

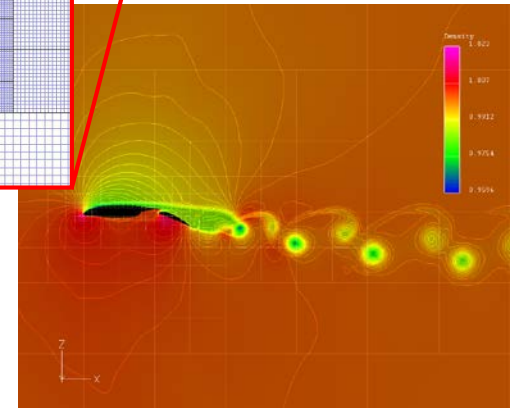
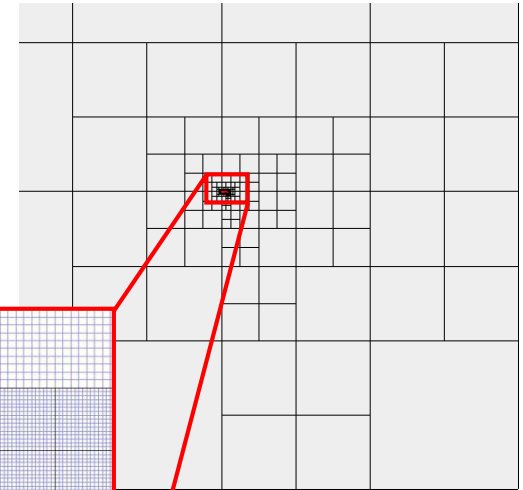
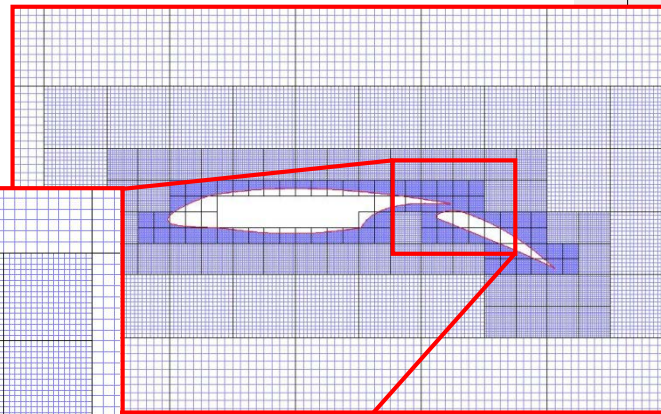
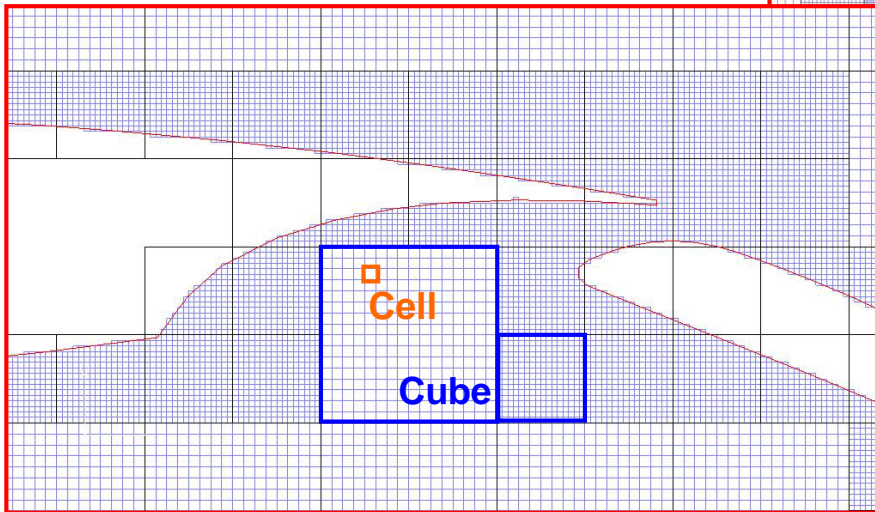
70s to 80s;
Euler/Re-av. N-S eqs. on Boundary-Fitted grid (Structured mesh) for accuracy and efficiency

TAS-Code
(Tohoku university Aerodynamic Simulation Code)
Practical tool for aircraft design

Development of Next-Generation CFD: **Building-Cube Method**

- Highly-dense computational mesh to remove the influence of modeling and mesh quality
- Simple algorithm due to Cartesian mesh
- Easy Parallelization due to 'Cube' concept
- Easy Mesh Generation, Movement, Refinement

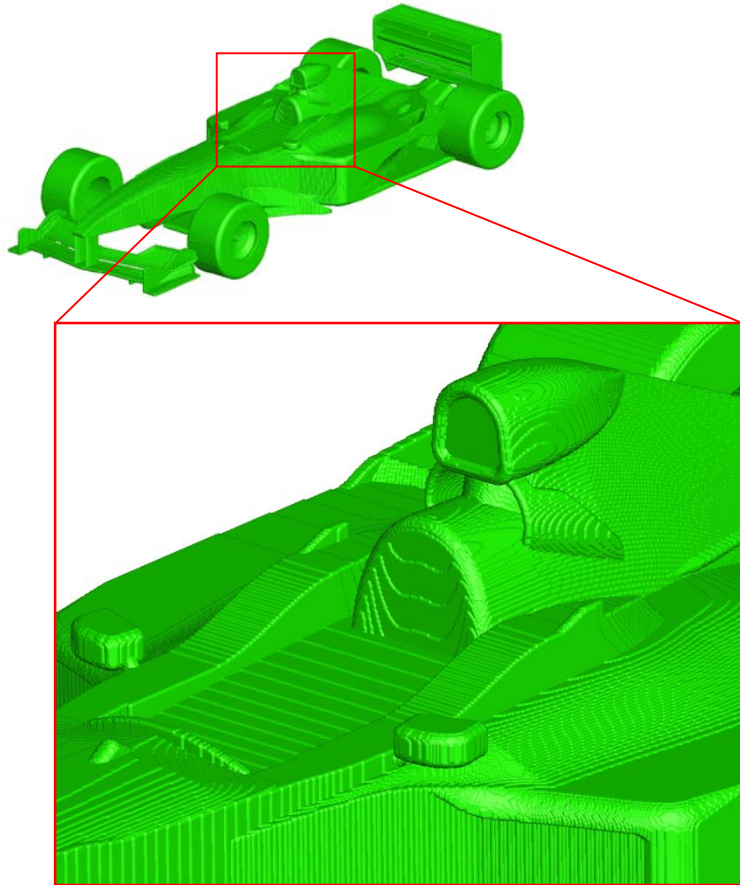
Each cube has equi-distant mesh cells



➤ Nakahashi, K., "High-Density Mesh Flow Computations with Pre-/Post-Data Compressions," AIAA Paper 2005-4876, 2005.

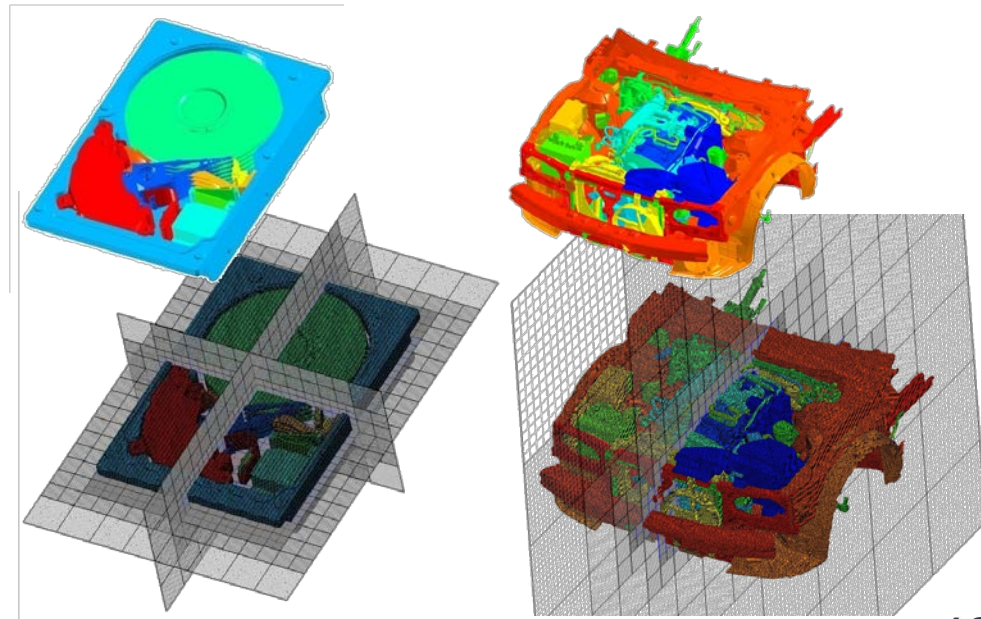
An example of Large-Scale BCM Meshing

→ Large-scale mesh is generated on PC (Xeon 2.2GHz 8 core)



#facet	1,189,898
#cubes	3,385
#cells	887,357,440
#cells in a cube	64 × 64 × 64
min. grid spacing	6.1e-4
time[min]	3.4
Memory Usage[MB]	254
Output data size[MB]	11.1

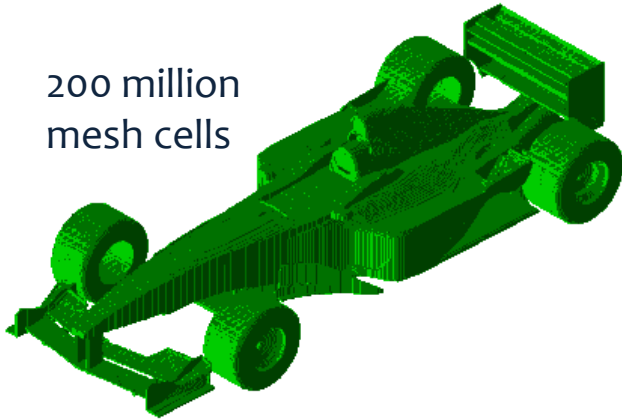
✓ Minimum cell scale is 2.8 mm in real size



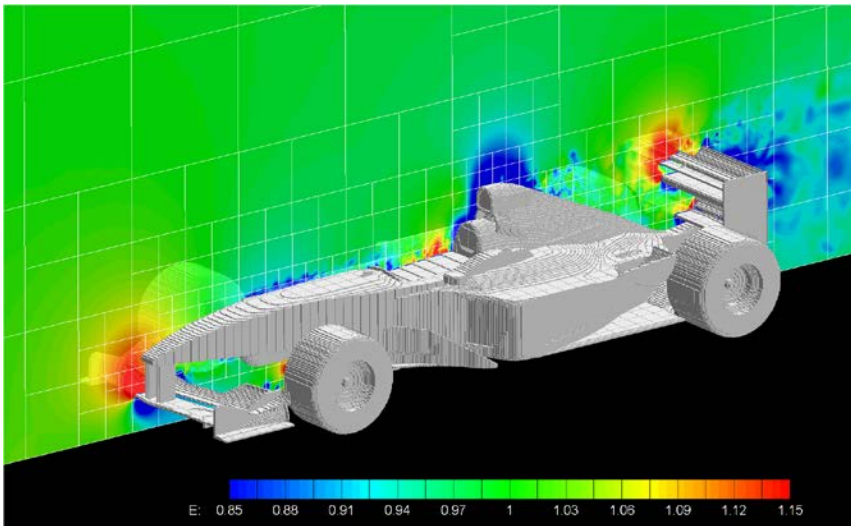
- Ishida, T., et al., "Efficient and Robust Cartesian Mesh Generation for Building-Cube Method," Journal of Computational Science and Technology, 2008.

→ Formula 1 racing car model

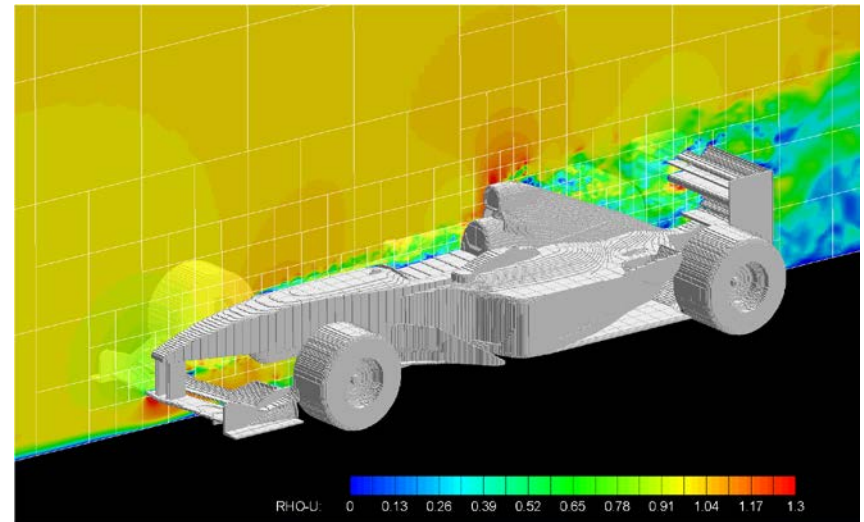
200 million
mesh cells



Reynolds number	2.6×10^6
Minimum spacing	7.32×10^{-4}
# of cell in cubes	32^3
Total # of cube	5,930
Total # of cell	194,314,240



Pressure Field



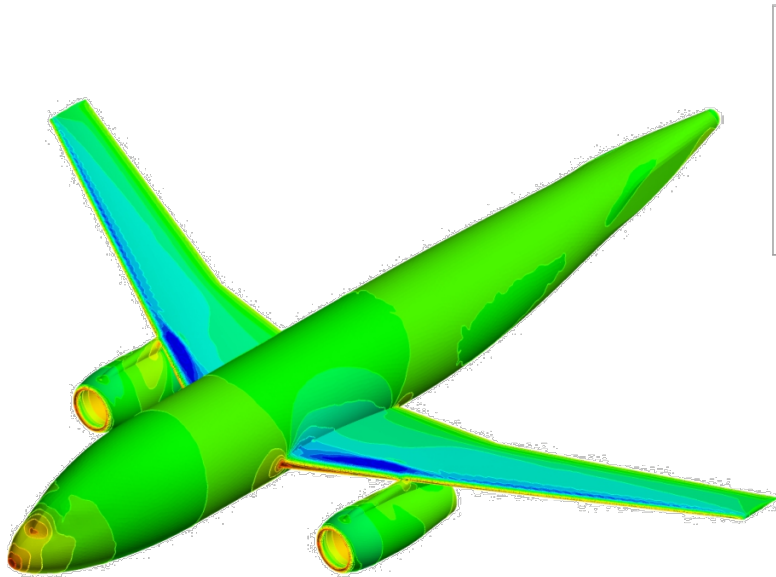
Velocity Field

➤ Takahashi, S., et al., "Parallel Computation of Incompressible Flow Using Building-Cube Method," Lecture Notes in Computational Science and Engineering, 2009.

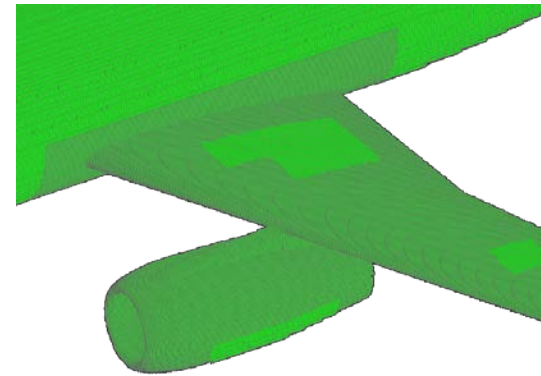
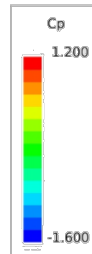
圧縮性流れ解析

➔ BCM Compressible Solver for Steady/Unsteady/Flutter

- Compressible Euler equations
- Cell-Center Finite Volume Method
- Approximate Riemann solver by HLLEW, and 3rd-order MUSCL
- Immersed boundary method with ghost cell approach
- Fast deformation of geometry (unsteady/flutter)



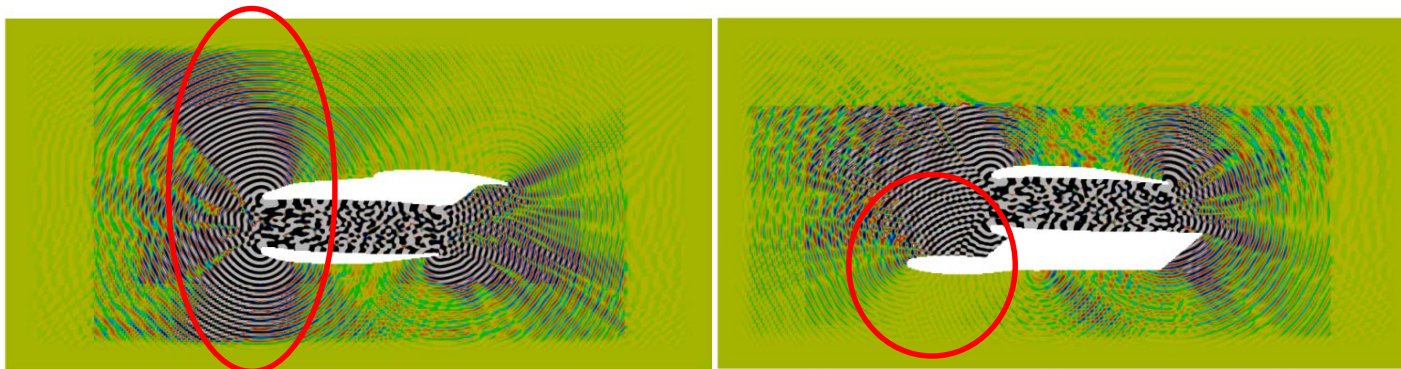
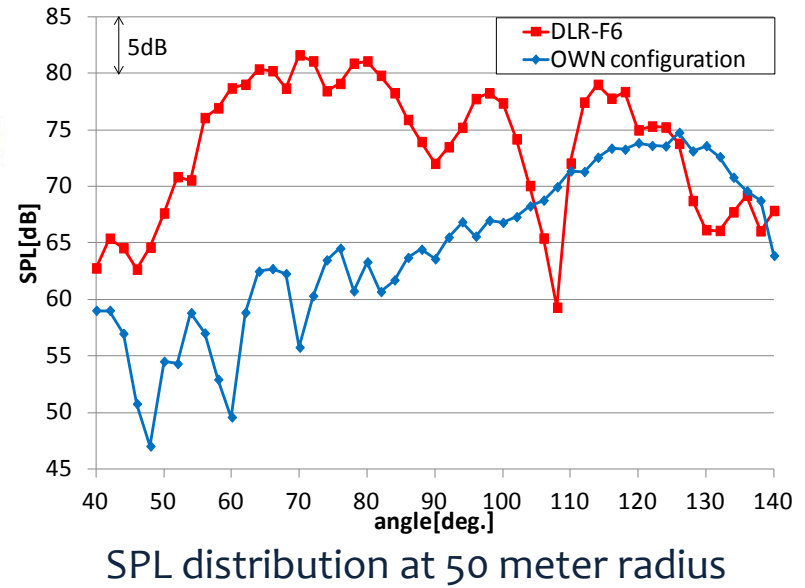
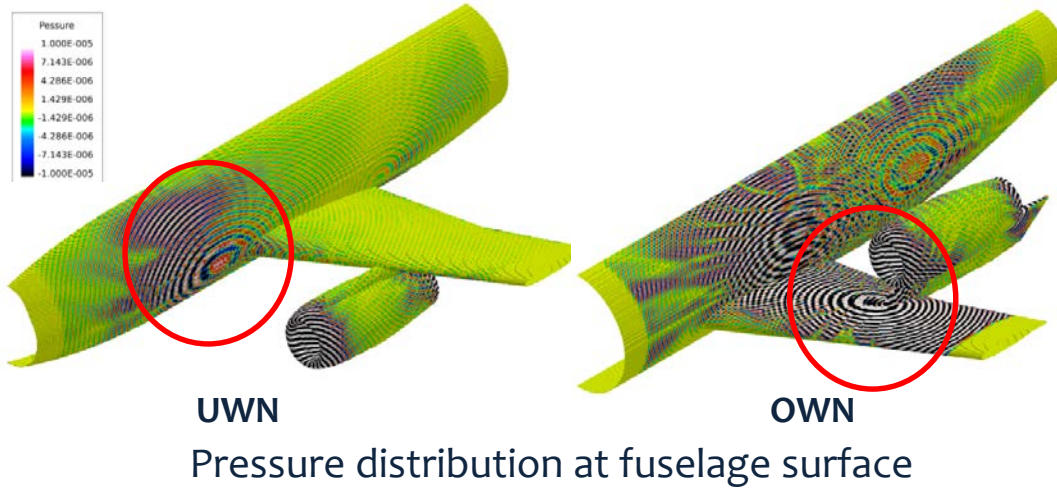
Euler computation around DLR-F6 model



Mach number [-]	0.7
Angle of attack [deg]	0.5
Number of cube cells in a cube	4,662
Total number of cells	19,095,552
Minimum cell size	0.00092 / length of fuselage
dt	1.0

- 西村ら, “Building-Cube Method による圧縮性Eulerソルバーの構築と航空機翼のフラッタ解析への応用,” 日本航空宇宙学会論文集, 2014.

- ➔ Comparison of fan noise propagation for conventional (UWN) and Over-The-Wing-mounted-engine (OTW) configuration
 - OTW can greatly reduce noise toward ground



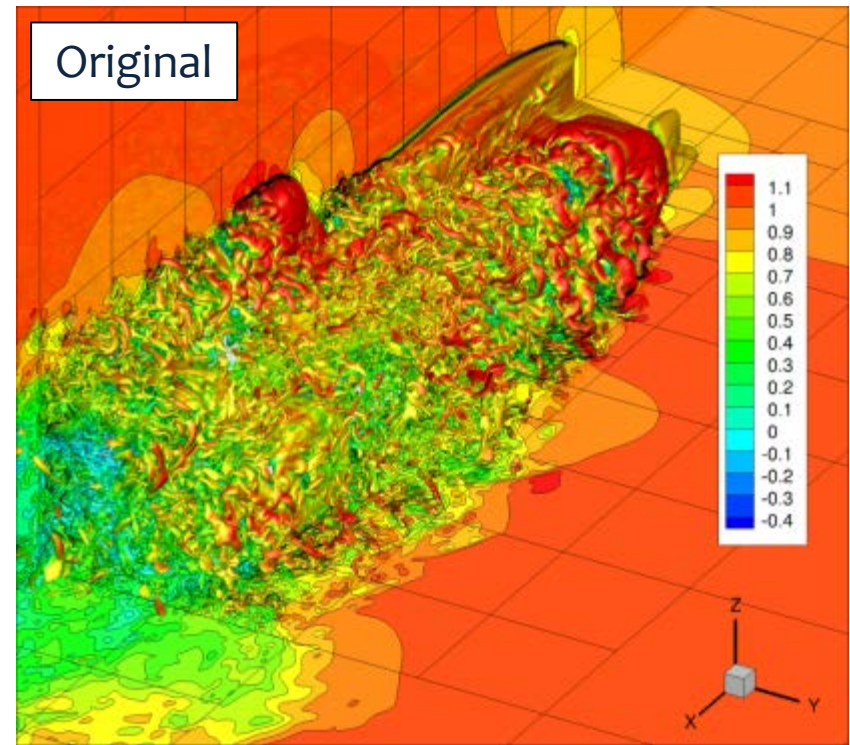
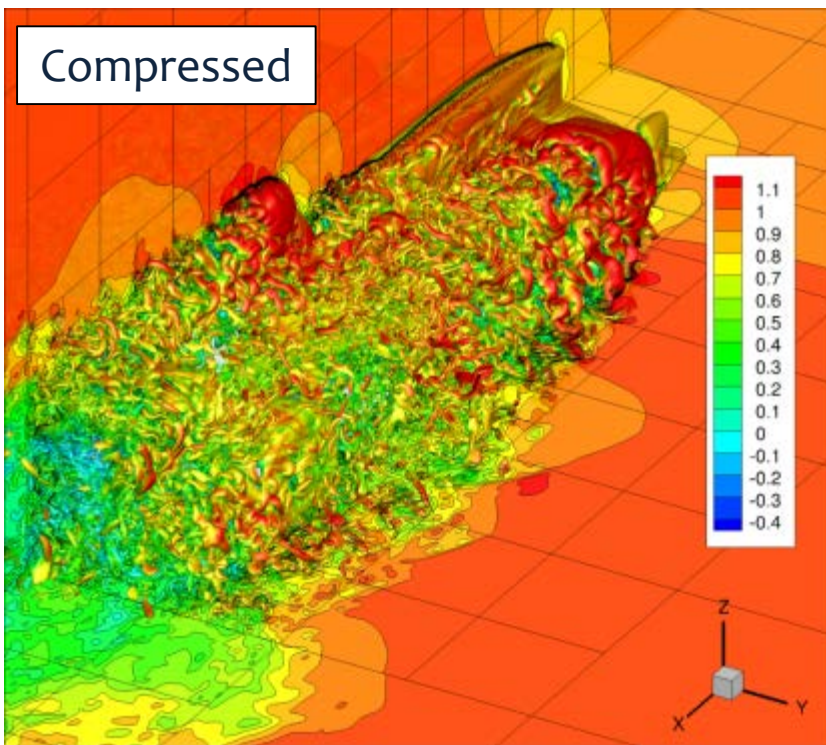
➤ Fukushima, Y., et al., "Code Development of Linearized Euler Equation on Block-Structured Cartesian Mesh for Complicated Geometries," AIAA Paper 2012-0832, 2012

データ圧縮(後処理)

➔ Reduction of large data generated by unsteady flow Computation using wavelet transform

- Vorticity is clearly preserved in compressed data.
- Compressed data size is 144 MB, while original data size is 3.88 GB.

RMSE	4.25E-04
Max. error	5.42E-03
Comp. ratio	27.0:1 (3.70%)

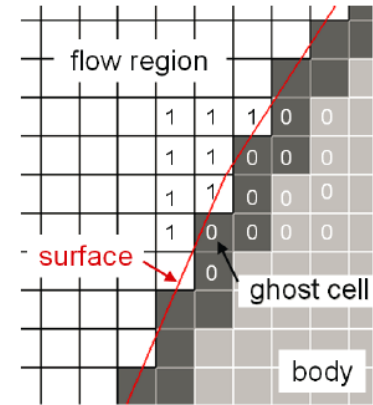


BCMの壁面境界条件(残された課題?)

➤ Staircase representation

$$g_{ghost} = \frac{\sum_{i(\text{adjacent cells})} (g_i \times flag_i)}{\sum_{i(\text{adjacent cells})} (flag_i)}$$

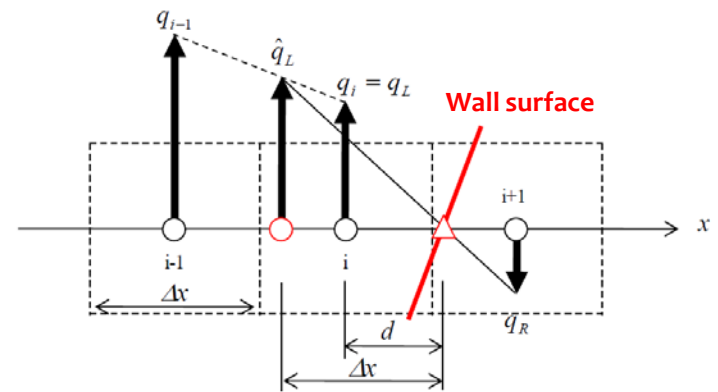
- Nakahashi, K., "High-Density Mesh Flow Computations with Pre-/Post-Data Compressions," AIAA Paper 2005-4876, 2005.



➤ Immersed boundary method (IBM) by Mittal

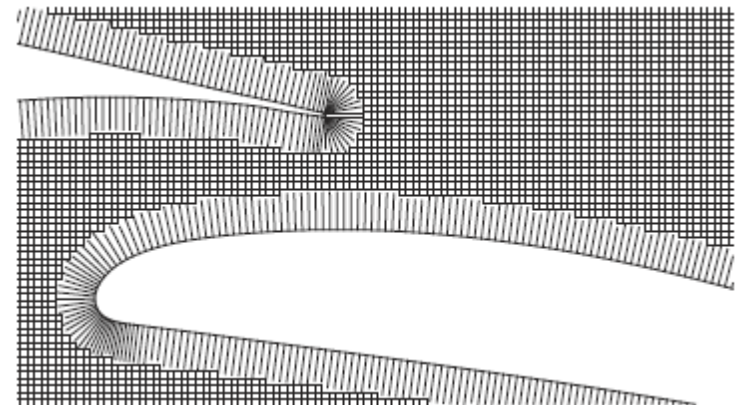
➤ Mittal IBM + wall model

- Deguchi A., et al., "Aeroacoustic Simulation of JAXA Landing Gear by Building-Cube Method and Non-compact Curle's Eqation," AIAA Paper 2012-388, 2012.
- Onishi K. et al. "Vehicle Aerodynamics Simulation for the Next Generation on the K Computer: Part 2 Use of Dirty CAD Data with Modified Cartesian Grid Approach," SAE International Journal, 2014



➤ Grid-less method

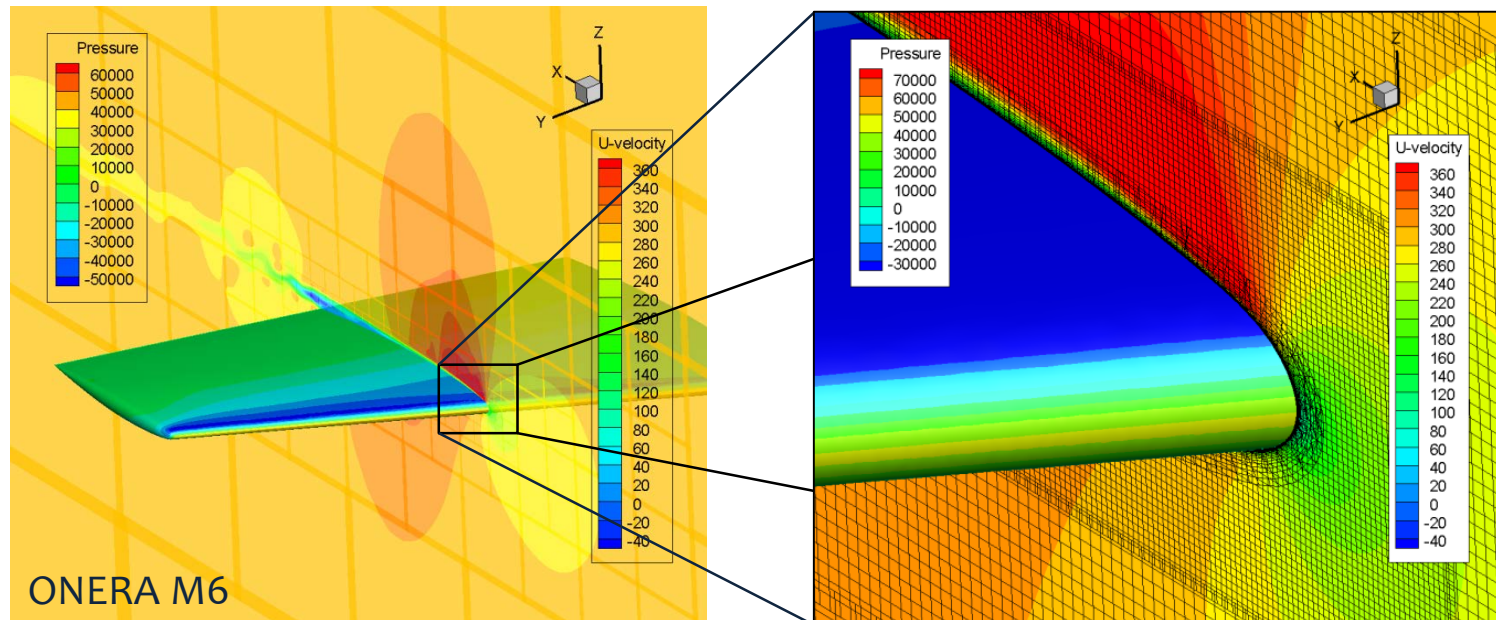
- Su, X., et al., "Cartesian mesh with a novel hybrid WENO/meshless method for turbulent flow calculations," Computer and Fluids, 2012.
- Ishida, T., et al., "A High-Resolution Method for Flow Simulations with Block-Structured Cartesian Grid Approach," AIAA Paper 2011, 2011.



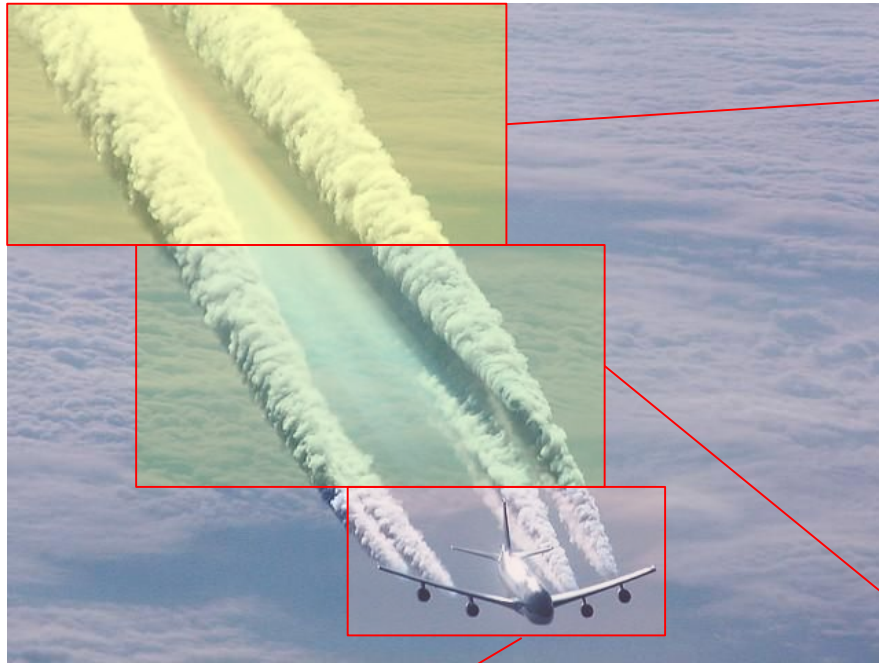
非構造格子とのカップリング(1)

非構造格子TASコードを境界層付近で使い，物体周りの 高レイノルズ数流れ解析ができるコードの開発

妥協点 : BCMの自動格子生成・Duty CAD対応応力が失われる
(結局，格子生成で苦勞する or ソルバーで苦勞する?)



非構造格子とのカップリング(2)



Near-field

Unstructured mesh compressible RANS solver (TAS code)

- HLLIW approx. Riemann solver with 2nd-order reconstruction
- LU-SGS implicit time integration
- SST turbulence model

Far-field

Cartesian mesh incompressible LES solver (Incompressible BCM code)

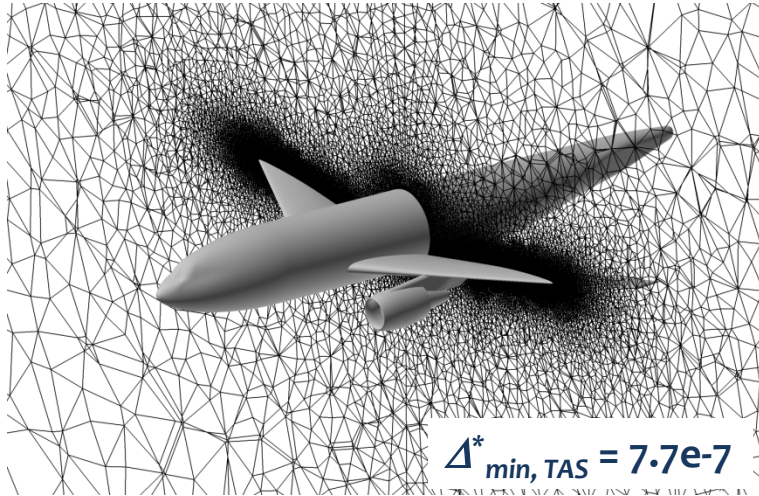
- 4th-order central difference scheme (Morinishi et al., JCP, 1998)
- 3rd-order Runge-Kutta
- Lagrangian dynamic SGS model

Mid-field

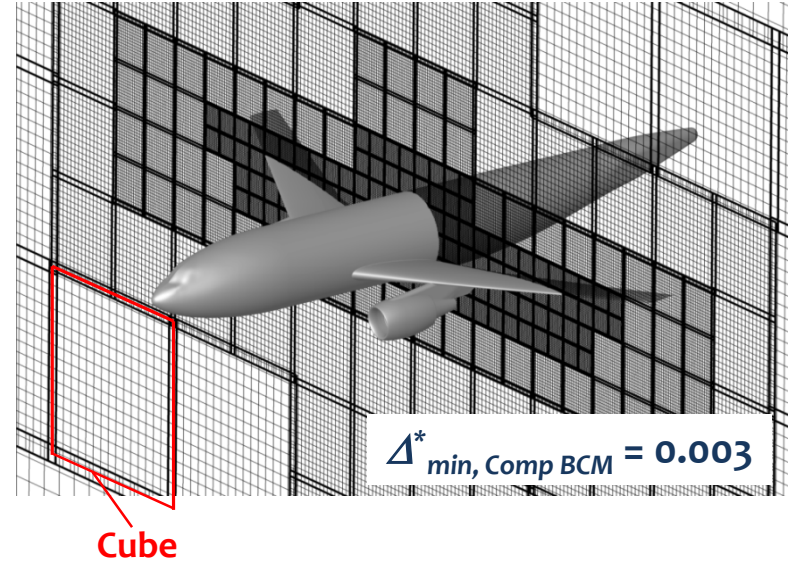
Cartesian mesh compressible LES solver (Compressible BCM code)

- HLLIW / 2nd-order central hybrid (Morinishi et al., JCP, 2013)
- 3rd-order Runge-Kutta
- Lagrangian dynamic SGS model

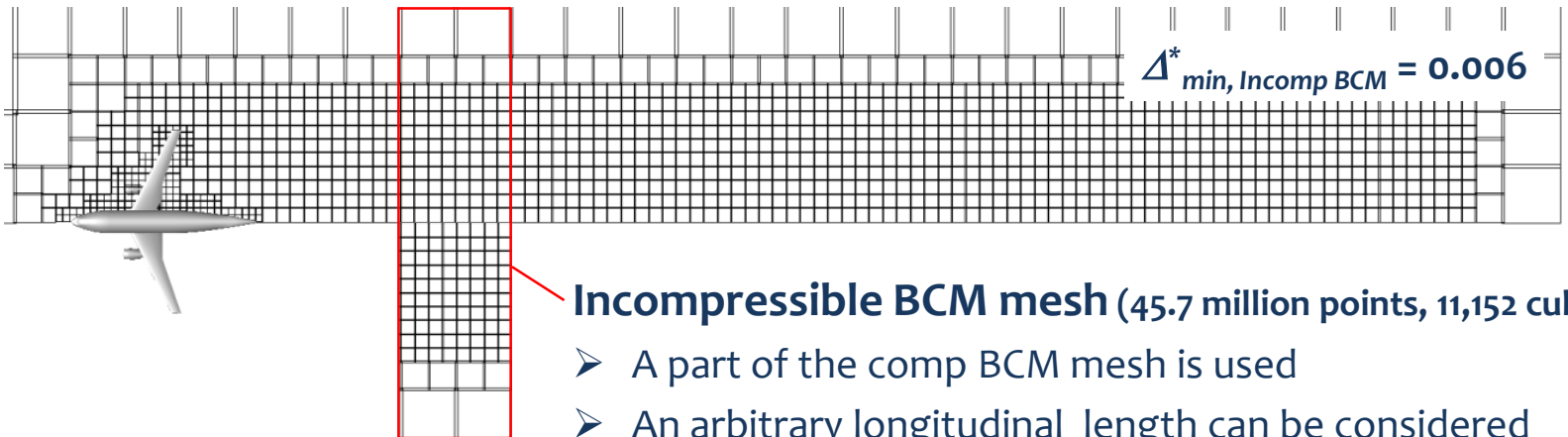
TAS mesh (11.4 million points)



Compressible BCM mesh (26.3 million points, 6,413 cubes)



Compressible BCM mesh



Incompressible BCM mesh (45.7 million points, 11,152 cubes)

- A part of the comp BCM mesh is used
- An arbitrary longitudinal length can be considered

BCM-TASカップリングによるDES (1)

Detached Eddy Simulation (DES)

$$\frac{D\tilde{\nu}}{Dt} = C_{b1}\tilde{S}\tilde{\nu} + \frac{1}{\sigma} [\nabla \cdot ((\nu + \tilde{\nu})\nabla\tilde{\nu} + c_{b2}(\nabla\tilde{\nu})^2)] - c_{w1}f_w \left[\frac{\tilde{\nu}}{\tilde{d}} \right] \quad \begin{array}{l} \text{Spalart-Allmarasモデル} \\ \text{(一方程式乱流モデル)} \end{array}$$

$$\tilde{d} = \min(d_w, C_{DES}\Delta)$$

生成項と崩壊項がバランスしたときに, Smagorinskyモデルと等価になる

Delayed DES

$$\tilde{d} = d_w - f_d \max(0, d_w - C_{DES}\Delta) \quad r_d = \frac{\nu + \nu_t}{\sqrt{U_{ij}U_{ij}}\kappa^2 d_w^2} \quad \begin{cases} f_d = 0 \text{ (境界層内)} \\ f_d = 1 \text{ (境界層外)} \end{cases}$$

$$f_d = 1 - \tanh[(8r_d)^3]$$

この f_d を境界層の判別に利用→境界層内はSAモデル, 境界層外はDynamic Lagrangianモデル, または, Coherent Structureモデル

• Dynamic Lagrangianモデル: モデル係数の平均を流跡線に沿って行う

• Coherent Structureモデル: $C_s = \frac{1}{20} |F_{CS}|^{3/2} \quad F_{CS} = \frac{\bar{W}_{ij}\bar{W}_{ij} - \bar{S}_{ij}\bar{S}_{ij}}{\bar{W}_{ij}\bar{W}_{ij} + \bar{S}_{ij}\bar{S}_{ij}}$

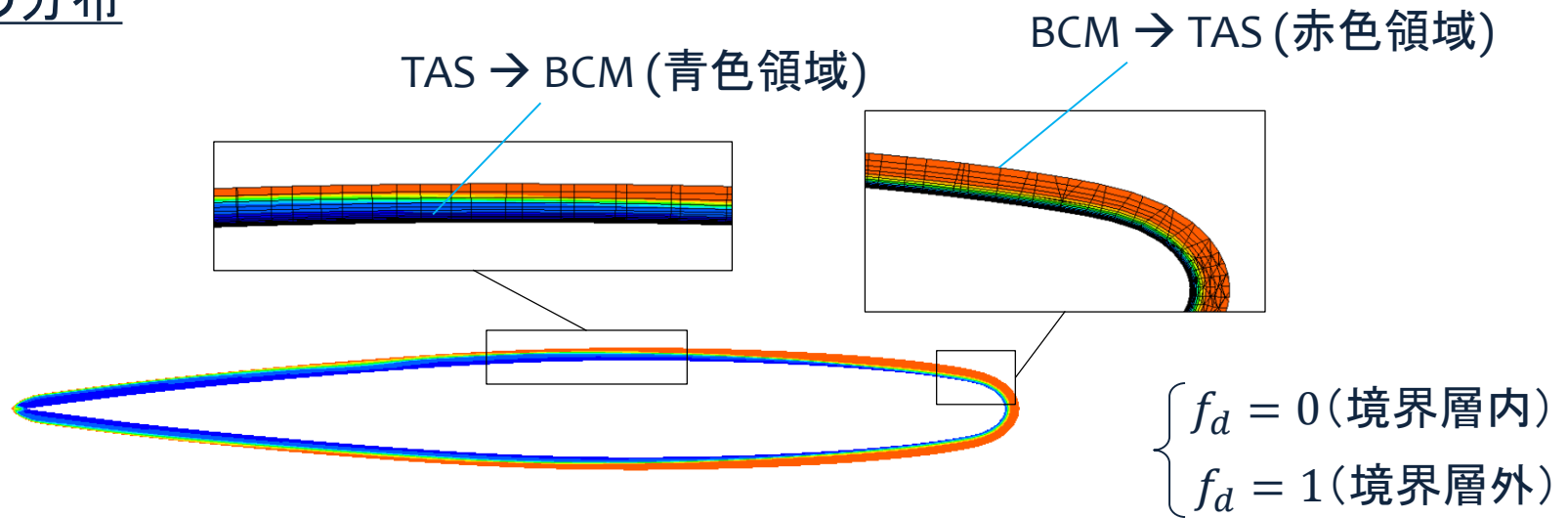
→ どちらのモデルも任意形状や渦流れに適用できる

BCM-TASカップリングによるDES (2)

流れ場の変数をBCM変数とTAS変数の荷重平均で表す

$$Q = f_d Q_{BCM} + (1 - f_d) Q_{TAS}$$

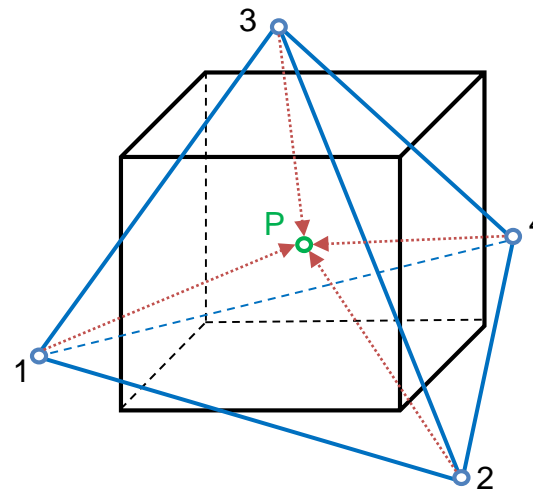
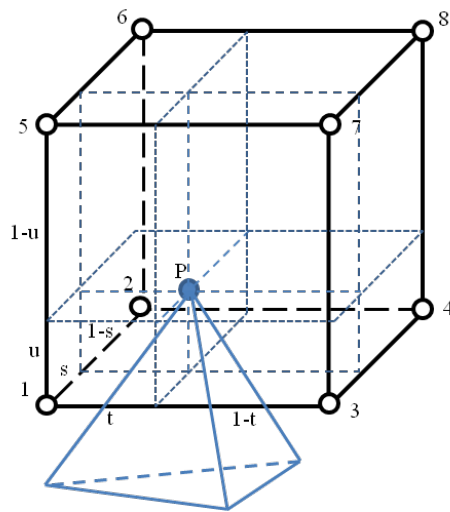
f_d の分布



- 境界層外縁でTASとBCMがスムーズに切り替わる
- TAS-BCMの情報交換を行う領域は f_d より流れ場から決まる

数値計算手法

	非構造格子(TAS)	直交格子(BCM)
支配方程式	圧縮性NS方程式	
乱流モデル	Spalart-Allmaras	Dynamic SGS
空間スキーム	HLLEW+線形再構築	2次精度中心差分 /HLLEWハイブリッド
時間スキーム	2次精度陰解法	3次精度Runge-Kutta
並列化	OpenMP	OpenMP



➤ TAS-BCM格子間の流れ変数のやりとりは線形補間

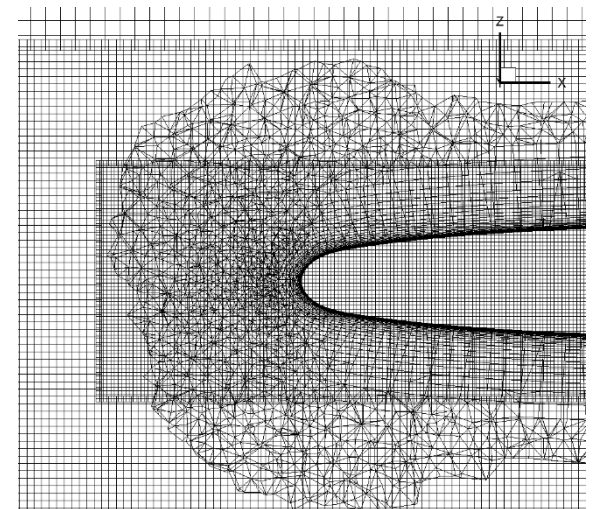
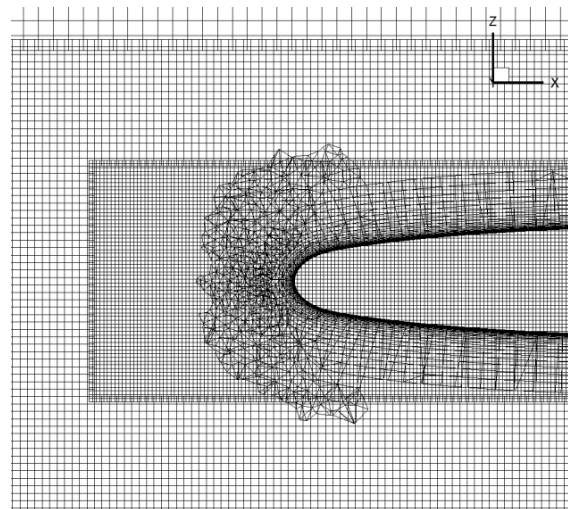
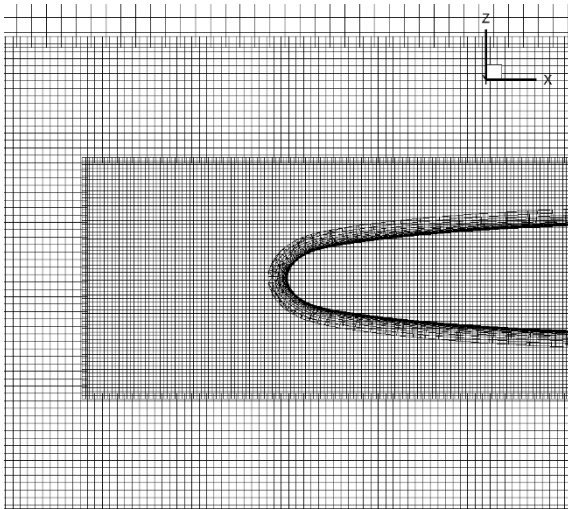
TAS-BCM格子の重ね方

BCM格子: 7634 cube, 3127万点

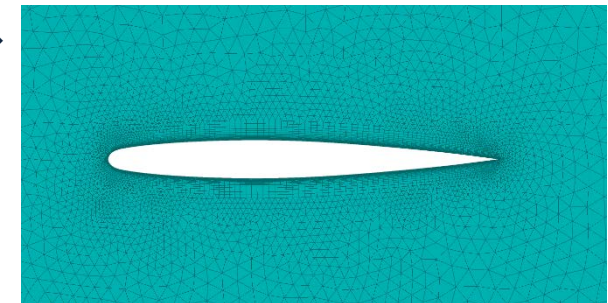
TAS格子: 77万点

128万点

140万点

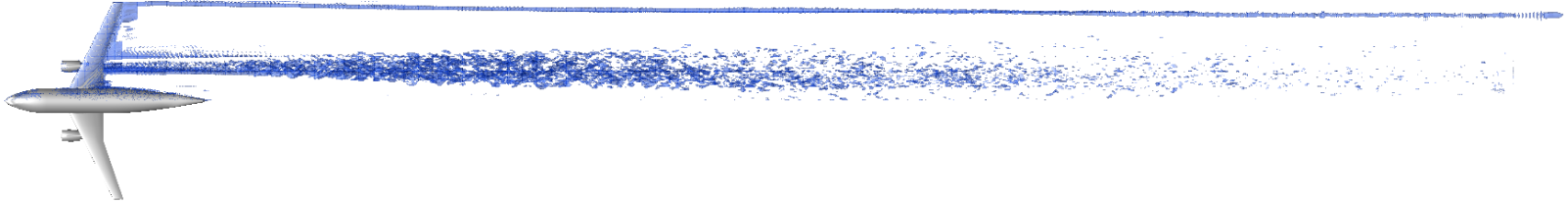


- 通常のTAS格子から余分な要素を取り除いて作成 →
- TAS格子は境界層を含む厚さが必要
- 薄いTAS格子でも格子点数は比較的多い
- MPI化した場合のTAS格子データの持ち方??

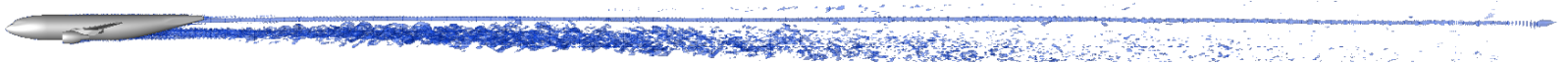


Iso-surface of axial vorticity

Top view



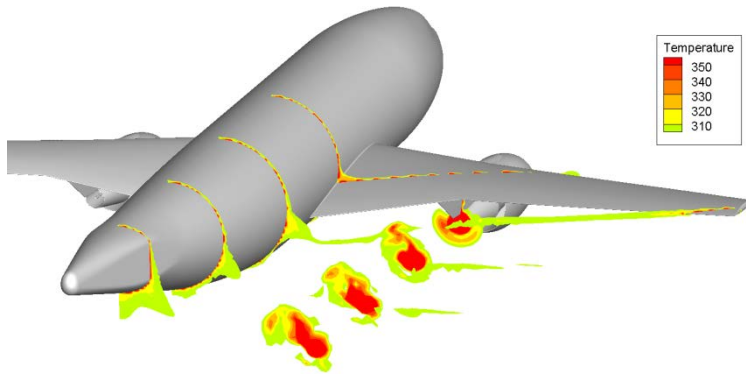
Side view



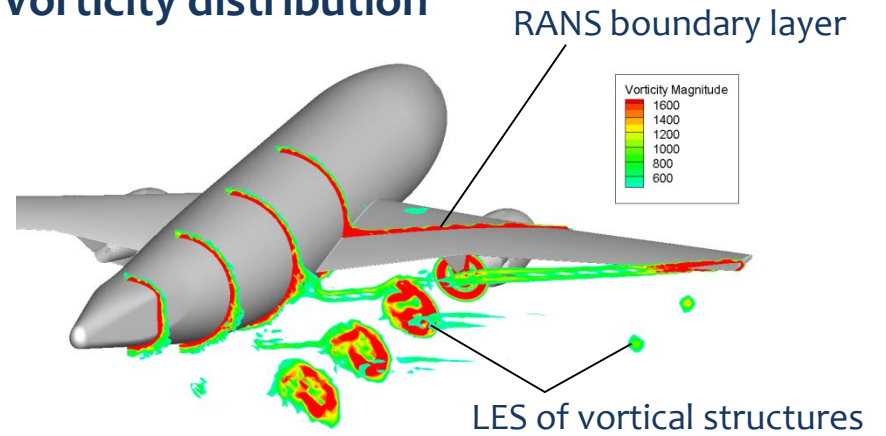
- Uniform Cartesian mesh preserves wing-tip vortices, while simulating diffusing jets

Jet and Tip Vortex

Temperature distribution



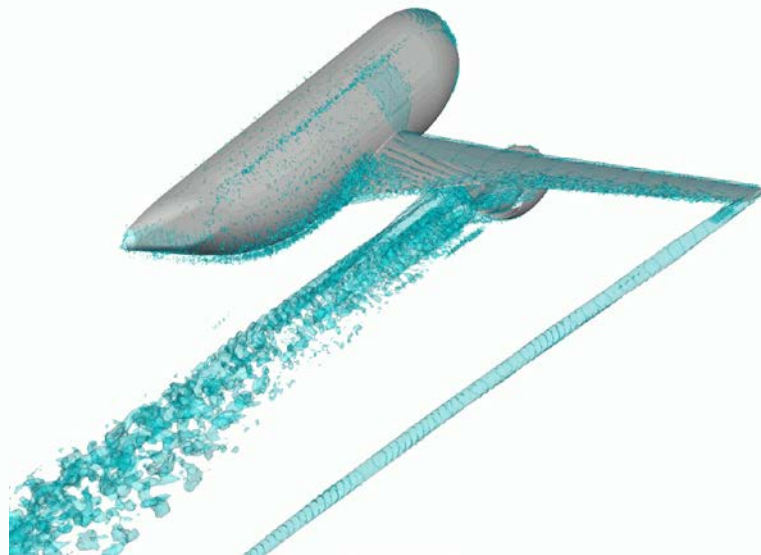
Vorticity distribution



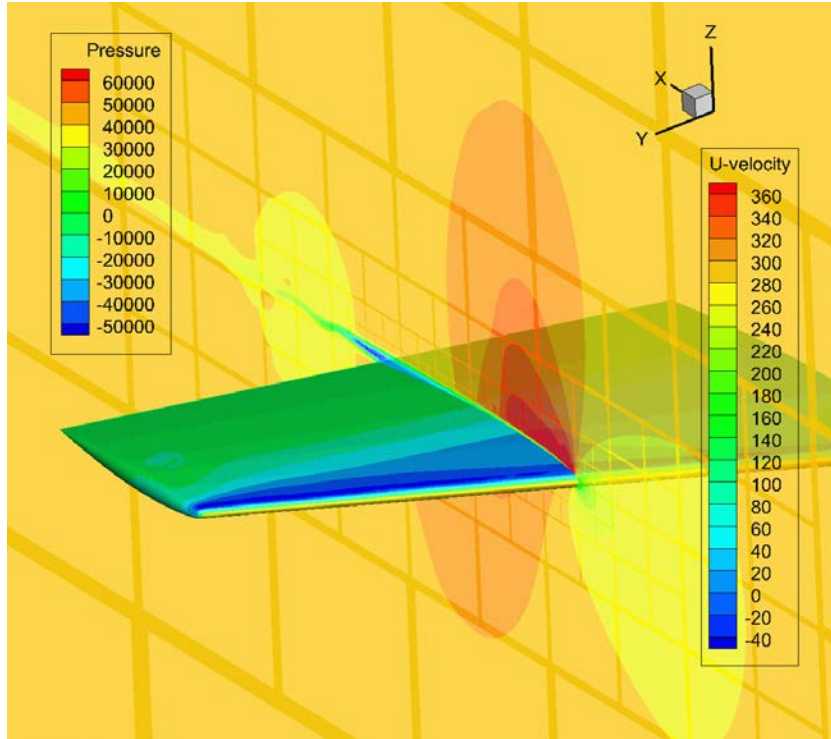
Temperature iso-surface



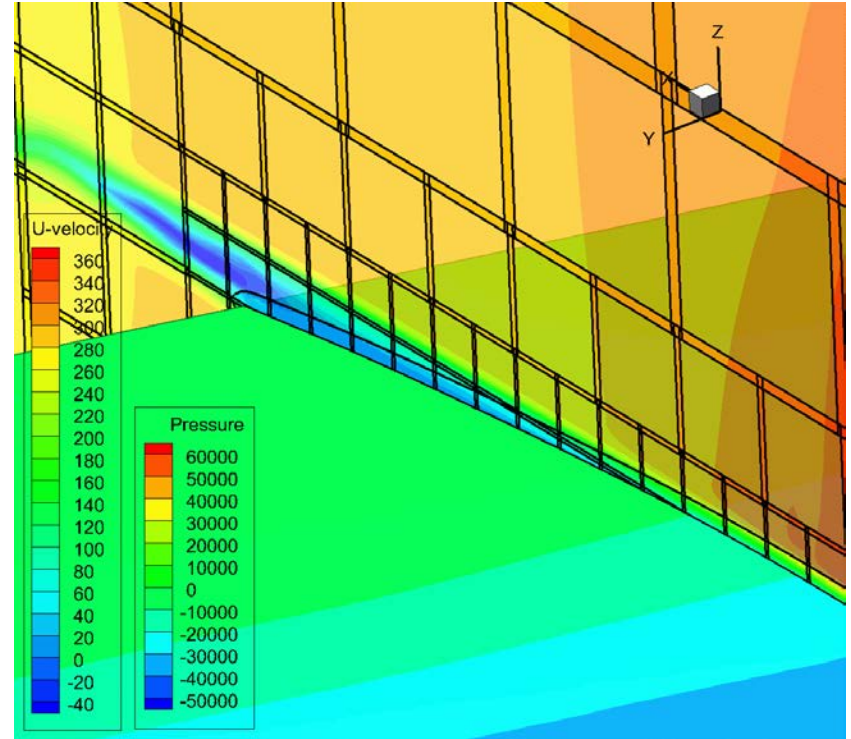
Vorticity iso-surface



ONERA M6全体



後縁付近



航空機まわり流れから後方乱気流までを解析できるようなコードをBuilding Cube Methodにより開発している

- 大規模解析ためのフレームワークとしてのBCMに期待
- 高レイノルズ数流れ解析では直交格子による境界層の扱いに工夫が必要であり、本研究では非構造格子とのカップリングで問題を回避(一時的?)
- 今後、動的計算負荷分散、解適合格子細分化などCube構造を生かした機能の実装を行っていく





<https://darkskydiary.wordpress.com/tag/contrails/>