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宇宙航空研究開発機構特別資料
JAXA Special Publication

第 2 回 EFD/CFD 融合ワークショップ
The 2nd Workshop on Integration of EFD and CFD

開催日　:平成 21 年 2 月 23-24 日

開催場所:宇宙航空研究開発機構(JAXA)

調布航空宇宙センター

2010 年 1 月
January 2010

宇宙航空研究開発機構
Japan Aerospace Exploration Agency

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The 2nd Workshop on Integration of EFD and CFD

第2回EFD/CFD融合ワークショップ

開催趣意書

従来、数値流体力学（Computational Fluid Dynamics, CFD）と実験流体力学（Experimental Fluid Dynamics, EFD）とは、研究所等の専門機関ではどちらかといえば別個の分野とみなされ、それぞれ人材もリソースも独立に、独自の立場で行われてきました。しかしながら、CFDは物理現象をモデル化して数値的に解を求めている以上、結果の妥当性を実験データを用いて検証する必要があり、その意味でCFDはEFDに一方的に依存していたと言えます。EFDもこれまでCFDに対して傍観者的な立場に終始してきたことは否めない一方、EFDにはEFD固有の不確かさがあり、また得られる情報にも制限が生じます。確実に言えることは、EFD/CFD単独で得られるデータの精度や信頼性には自ずから限界が生じるということでしょう。

一方、大学の研究室等においては、実験と計算の両面からのアプローチは日常的な手段であり、実験と計算の単純な比較から考察をして行くという意味ではEFDとCFDは常に密接な関係にあります。

このような現状に鑑み、研究所においては、二元論的な考え方を改め双方の信頼性を向上させ真に実用に供するツールとなすために、また、大学等においては、単純比較を超えたより深い洞察・知見を得られるようにするため、EFD/CFDの互いの問題点の補完や新たな枠組みの構築によって得られるシナジー効果を見いだすことが重要ではないでしょうか。

本ワークショップはこのようなEFDとCFDの融合をテーマとし、流体力学に携わる研究者や技術者が講演やディスカッションを通してその必要性・重要性について認識を深め、かつ知見を広げることを目的としております。

第1回会合は、2008年2月26日（火）に宇宙航空研究開発機構（JAXA）調布航空宇宙センターにおいて開催されました。しかし、参加者を限定した非公式なワークショップであったことから、今回は規模を拡大して広く参加を呼びかけました。国内招待講演については、航空宇宙に限らず様々な分野から講演をお願いし、興味深くかつ非常にバリエーションにとんだ内容になったと自負しております。さらに本分野において海外で先駆的な研究活動を行ってこられた、Rice大学のAndrew Meade教授、およびBoeingのEdward Tinoco博士のお二方による特別講演も企画いたしました。

このワークショップが、EFD/CFD融合という古くて新しいテーマに関して情報交換をするよい機会となり、新たな発想による研究開発活動が国内外でより一層展開されるようになれば、主催者として何よりの喜びです。また、本ワークショップは今後も継続させていく予定ですので、内容についてご意見やご提案等ございましたらぜひともお知らせいただきたく、宜しくお願い申し上げます。

平成 21 年 2 月 23 日

第 2 回 EFD/CFD 融合ワークショップ実行委員会 委員長
宇宙航空研究開発機構 研究開発本部　松尾 裕一
東北大学 流体科学研究所　大林 茂

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The 2nd Workshop on Integration of EFD and CFD

Program

Feb. 23 (Mon.), 2009		
13:00–13:05	松尾 裕一 (JAXA) Yuichi Matsuo (JAXA)	Opening Address
Session 1 <JAXA Keynote Speech>		司会: 松尾 裕一 (JAXA) Chairperson: Yuichi Matsuo (JAXA)
13:05–13:35	渡辺 重哉 (JAXA) Shigeya Watanabe (JAXA)	A System Concept for EFD/CFD Integration: JAXA Digital/Analog Hybrid Wind Tunnel
Session 2 <Invited Lecture#1>		司会: 松尾 裕一 (JAXA) Chairperson: Yuichi Matsuo (JAXA)
13:45–14:45	Andrew Meade (William Marsh Rice University, USA)	Reducing Uncertainty in EFD and CFD Through Data/Model Fusion
14:50–15:50	Edward N. Tinoco (Boeing Commercial Airplanes , USA)	Validation and Minimizing CFD Uncertainty for Commercial Aircraft Applications – The Integration of EFD and CFD
Panel Discussions		コーディネータ: 吉田 憲司 (JAXA) Coordinator: Kenji Yoshida (JAXA)
16:00–18:00	Can EFD/CFD Integration Minimize Uncertainty? Panelists: Andrew Meade (Rice Univ.) Edward N. Tinoco (Boeing Commercial Airplanes) 佐宗 章弘 Akihiro Sasoh (Nagoya Univ.) 越智 章生 Akio Ochi (Kawasaki Heavy Industries) 口石 茂 Shigeru Kuchi-Ishi (JAXA)	
18:00–20:00	Banquet (JAXA Restaurant)	

Feb. 24 (Tue.), 2009		
Session 3 <Invited Lecture#2>		司会: 松尾 裕一 (JAXA), 大林 茂 (東北大流体研) Chairperson: Yuichi Matsuo (JAXA) and Shigeru Obayashi (Tohoku Univ.)
10:00–10:40	佐宗 章弘(名大工) Akihiro Sasoh (Nagoya Univ.)	普段着のEFD/CFD連携～超音速抗力低減を題材として～ This is Our Usual EFD/CFD Collaboration– An Example in Supersonic Drag Reduction Study
10:40–11:10	加藤 千幸 (東大生産研) Chisachi Kato (Univ. Tokyo)	流体から発生する音の数値解析と実験計測 Numerical Computation and Experimental Measurement of Aerodynamic Noise
11:10–11:50	伊藤 貴之 (お茶の水女子大) Takayuki Ito (Ochanomizu Univ.)	実空間と時空間における流体可視化 Flow Visualization in Real and Time Spaces
11:50–12:20	坪倉 誠 (北大工) Makoto Tsubokura (Hokkaido Univ.)	自動車空力分野におけるEFD・CFD技術の動向と非定常空力シミュレータの開発 Current Status of EFD/CFD Techniques for Road Vehicle Aerodynamics and Development of the Unsteady Aerodynamic Simulator
12:20–13:30	Lunch	
13:30–14:10	樋口 知之 (統計数理研) Tomoyuki Higuchi (Institute of Statistical Mathematics)	逐次データ同化： シミュレーションと観測データのリアルタイム統融合をめざして Sequential Data Assimilation: Online Information Fusion Platform for Simulation and Observation Data
14:10–14:50	谷 泰寛(九大工) Yasuhiro Tani (Kyushu Univ.)	再使用型宇宙往還機に向けた研究における EFD/CFD の取り組み EFD/CFD Activities in Research for Reusable Launch Vehicles
Session 4 <Technical Session>		司会: 相曽 秀昭 (JAXA) Chairperson: Hideaki Aiso (JAXA)
15:00–15:30	保江 かな子 (東北大院) Kanako Yasue (Tohoku Univ.)	Discontinuous Galerkin 法を用いた AGARD-B 標準模型の静的空力弾性解析 Static Aeroelasticity Analysis of AGARD-B Wind Tunnel Calibration Model Using Discontinuous Galerkin Method
15:30–16:00	加藤 博司 (東北大院) Hiroshi Kato (Tohoku Univ.)	実大気環境を考慮した後方乱気流予測技術 Prediction of Wake Turbulence under Actual Atmospheric Condition
16:00–16:30	橋本 敦 (JAXA) Atsushi Hashimoto (JAXA)	JAXAデジタル/アナログ・ハイブリッド風洞: デジタル風洞の開発 JAXA Digital/Analog Hybrid Wind Tunnel: Development of Digital Wind Tunnel
16:30–17:00	藤田 直行 (JAXA) Naoyuki Fujita (JAXA)	JAXAデジタル/アナログ・ハイブリッド風洞: アナログ風洞の高速化 JAXA Digital/Analog Hybrid Wind Tunnel: Speed-Up Technique of Analog Wind Tunnel
17:00–17:05	大林 茂 (東北大流体研) Shigeru Obayashi (Tohoku Univ.)	Closing Address

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A System Concept for EFD/CFD Integration: Digital/Analog Hybrid Wind Tunnel

Shigeya Watanabe

Wind Tunnel Technology Center
Aerospace Research and Development Directorate
Japan Aerospace Exploration Agency (JAXA)

The 2nd Workshop on EFD/CFD Integration
Feb. 23, 2009 at JAXA Chofu Aerospace Center, Tokyo, Japan

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Contents

- Background, Motivation, and Objectives
- “Digital-Analog Hybrid Wind Tunnel”
  - Concept
  - System Architecture
- Technical element developments for Hybrid WT
  - Digital WT
  - Analog WT: Acceleration of reduction of flow imaging data
  - Integration of EFD and CFD
- Summary

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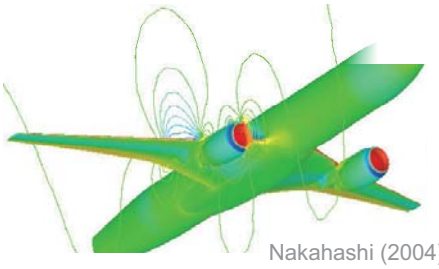
From “EFD and CFD” to Integrated EFD/CFD

■EFD: Analog, Real
Experimental Fluid Dynamics
(Wind tunnel test)

■CFD: Digital, Virtual
Computational Fluid Dynamics

Two major methods for aerodynamic characteristics prediction

Pressure measurement by PSP



Nakahashi (2004)

■Integration of EFD/CFD:
(or fusion, synergy)
- More than simple collaboration
- Aiming a new world where 1 + 1 > 2

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Motivation 1

Challenges of EFD & CFD in Aerodynamic Prediction

■EFD side:
- ✓Differences from real flight condition: Re number, Wind tunnel wall/support, Model deformation, etc.
- ✓Restriction of measurement items: Mainly, force/moment/discrete pressure. Additionally, flow visualizations and quantitative image measurements (PIV, PSP).
  - ⇒ Difficulties in understanding flowfield and troubleshooting
- ✓Relatively long period of a whole WT test campaign including model manufacturing.

Need for a unified platform to simultaneously solve both challenges.

■CFD side:
- ✓Reliability is always a concern, especially in turbulence, transition, separation, and reacting flow.
  - ⇒ Validation by experiments required.
- ✓Long calculation time (low data productivity) for high-fidelity CFD.
- ✓Higher skill and long time for grid generation required.

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Motivation 2

Challenges in EFD/CFD comparison

Ex.) Typical comparison

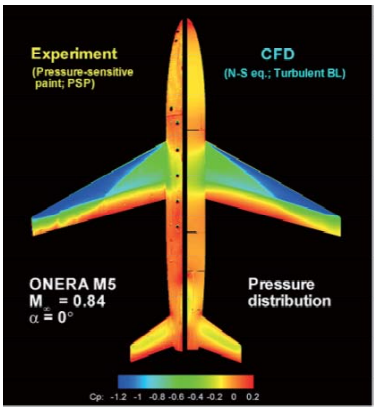
Discrepancies due to wind tunnel setting uncertainty

	EFD	pretest CFD
Mach number	0.904	0.9
Re number	2.1×10^6	2.0×10^6
Angle of attack	2.6° (including deflection of balance and sting)	2.0° (= setting angle)
Model configuration	Designed config. + deformation due to aero. load	Designed configuration
Boundary condition	With WT wall and sting	Model alone in freestream
Boundary layer transition location	Natural or forced transition	Fully laminar/ turbulent or fixed or predicted
Uncertainty	CD: ±0.0005	???

Unknown if not measured

Methodology not established

EFD (PSP) CFD



-with deformation of balance/sting	-no deformation of balance /sting
-with model deformation	-No model deformation
-with wall/sting	-with sting
-Natural transition	-Fully turbulent

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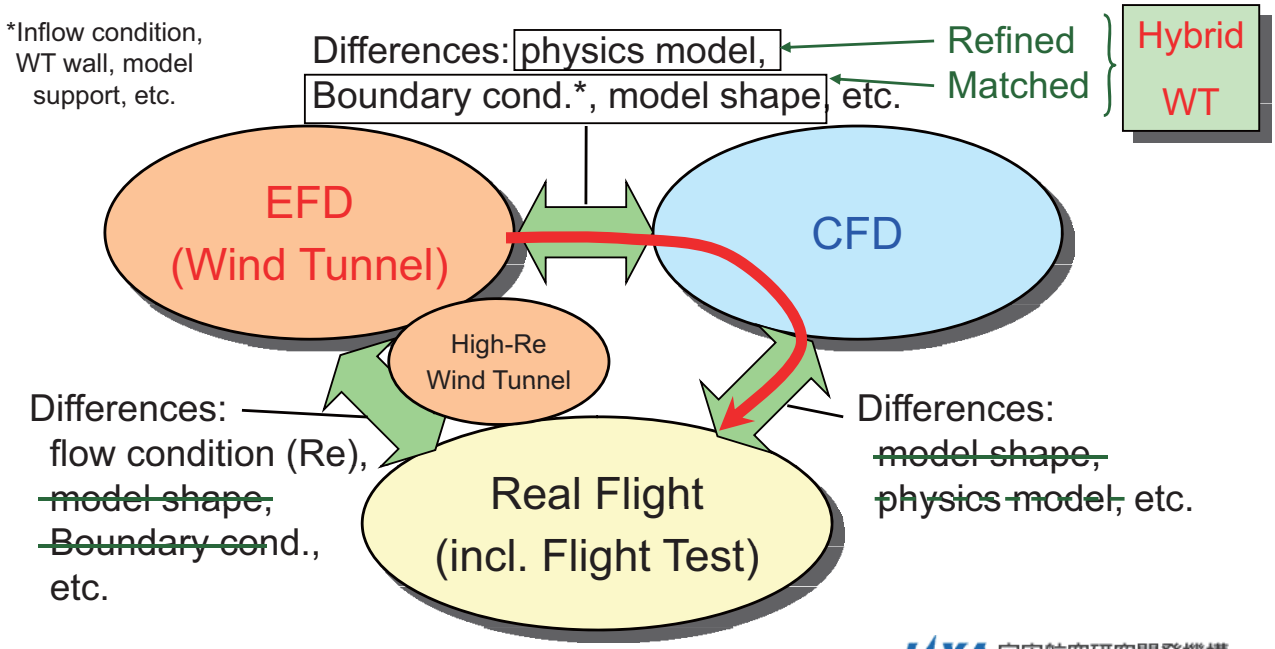
Motivation 3

Prediction of Aero. Characteristics at Real Flight

Goal of EFD & CFD in design: To predict aerodynamic characteristics at real flight condition accurately and effectively



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Digital/Analog Hybrid Wind Tunnel: Objectives

- Innovation of both EFD and CFD technologies through EFD/CFD integration.
- Reduction of cost and risk and improvement of accuracy and reliability of aerodynamic data in aerospace vehicle development.

⇒ Improved contribution to developments of Japanese airplanes such as MRJ and other JAXA projects.

Japanese Regional Jet, MRJ

Silent Supersonic Technology Demonstrator, S^{3}TD (JAXA)

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NASA Langley : Virtual Diagnostics Interface (ViDI) System

R. Schwartz, G. Fleming 2008

- Features and functions:
  - 3D-CAD-based virtual diagnostics system for experiment design
    - ✓ Optimization of measurement planning using virtual mockup
    - ✓ Real-time comparison and visualization of CFD and WT data (LiveView3D)
  - Similar systems are not known in other industrial wind tunnels in the world.

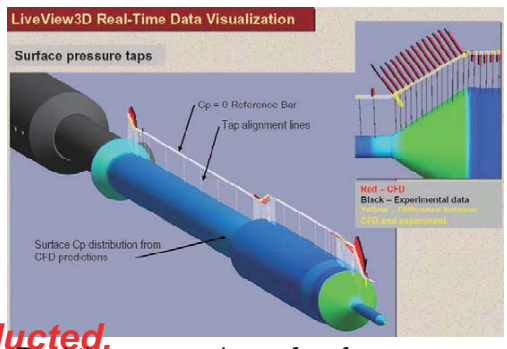
Superiority of the present Hybrid WT

- Technical disadvantages:
  - Data comparison relatively difficult due to different data formats for WT and CFD.

    ⇒ Unified data format, etc.
  - CFD has a secondary role (not necessarily conducted). ***⇒ Pretest CFD always conducted.***
  - No data fusion between WT and CFD data

    ⇒ EFD/CFD integration

Evaluation of PSP setting using 3-D CAD



Real-time comparison of surface pressure distribution between EFD and CFD

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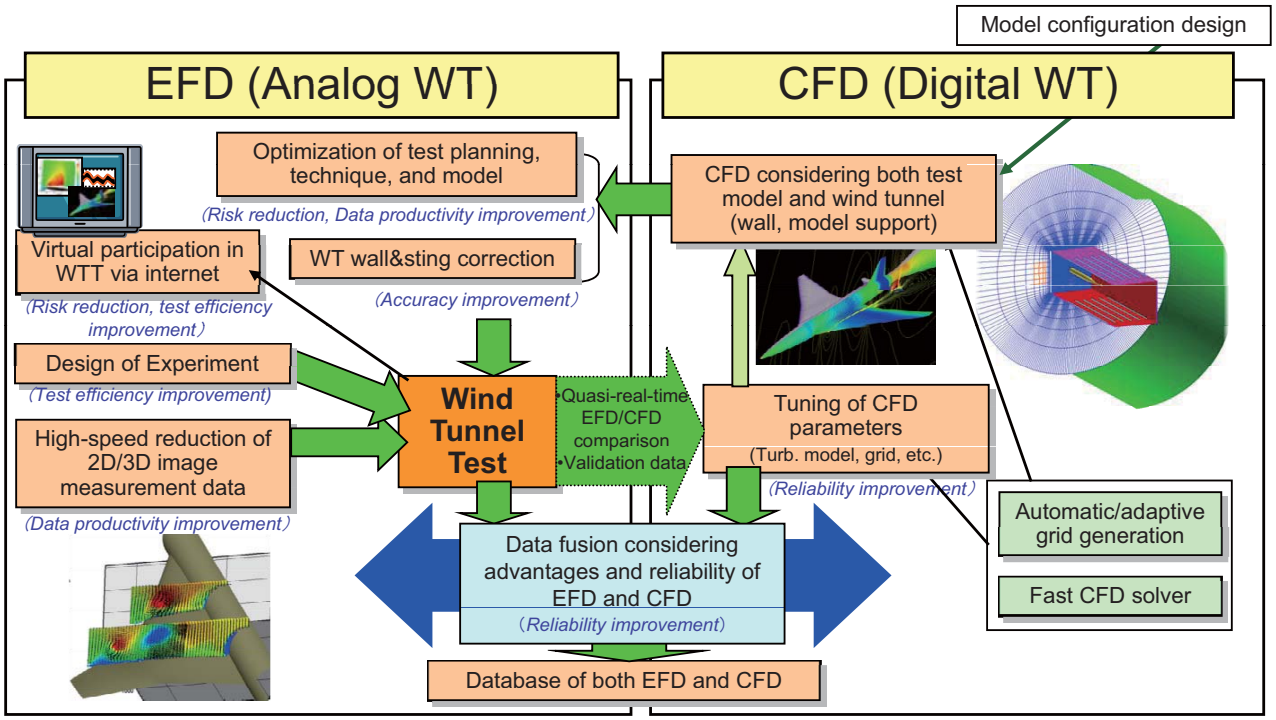
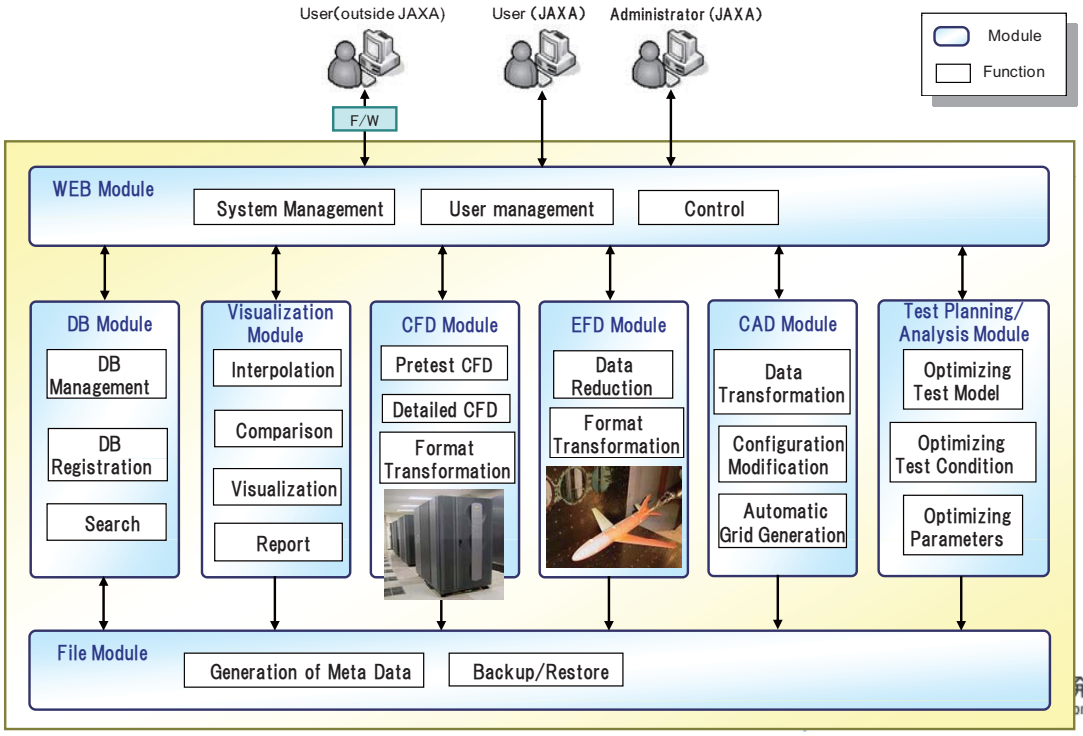
Digital/Analog Hybrid Wind Tunnel: Concept



Expanding the technology integrating experiment and numerical simulation to other fields

Digital/Analog Hybrid Wind Tunnel: System Architecture

- User access via Web.
- Raw EFD/CFD data stored in a self-descriptive data format with meta data stored in a XML-database.



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Development of Digital Wind Tunnel

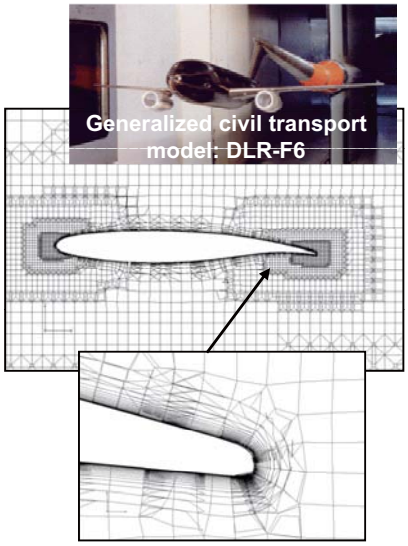
■Requirements for Digital WT

Fastness ← **Optimization of model and experimental planning by pretest CFD**

Solution: Automatic grid generator
+ New high-speed solver (**FaSTAR**)

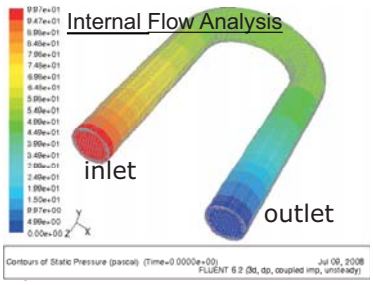
Accuracy ← **- Accurate correction of interaction by wall and sting interaction**
- Most probable aero. characteristics prediction based on both EFD/CFD

Solution: TAS* code (an existing RANS code) or FaSTAR
*TAS: Tohoku University Aerodynamics Simulation



■Status: Automatic grid generator using Cartesian grid technique and FaSTAR

- ✓Grid around an airplane model with 10^7 grid points can be constructed within ten min. using a regular PC.
- ✓The capability of the grid generator has been expanded to internal flow calculation.
- ✓In development of FaSTAR, a NS solver for laminar flow has been completed.



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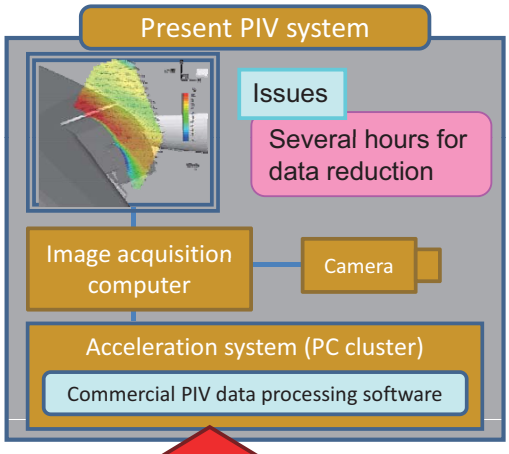
High-speed data reduction of imaging techniques

■Objective: to improve data productivity of Analog WT by accelerating data reduction for PIV and PSP images.

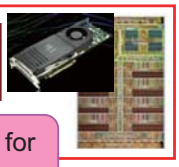
Ex)

Acceleration of PIV data reduction



Acceleration of commercial software

Accelerator (Cell, GPGPU, etc.)



Goal: Several minutes for data reduction

Preliminary test using Cell shows a possibility of ten-times faster data reduction.

Accelerator: **Cell** (High performance CPU developed by IBM/Toshiba/Sony) is the most promising candidate.

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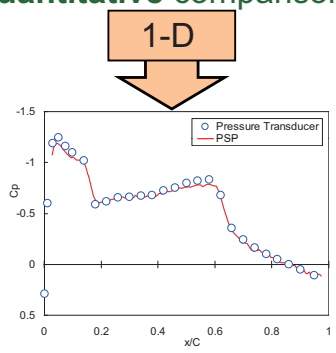
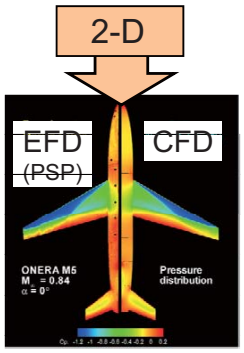
EFD/CFD Integration Techniques (1/3)

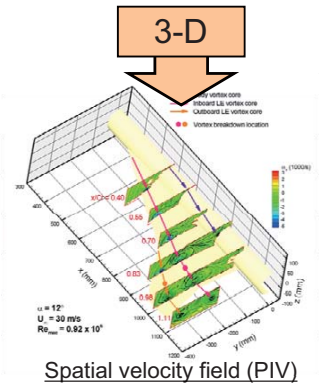
- Data comparison techniques
  - Objectives: ・Supporting rapid evaluation of the WT data during the test
    ・Clarifying technical problems of both EFD/CFD
  - **Quantitative** comparison:



Chordwise press. distribution

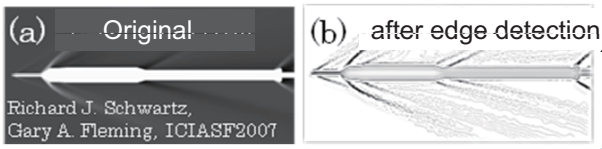


Surface press. distribution



Spatial velocity field (PIV)

  - **Qualitative** comparison: Feature extraction methods such as edge detection, template matching for extracting flow features (vortex, separation, shock, etc.)



Edge detection for a Schlieren image

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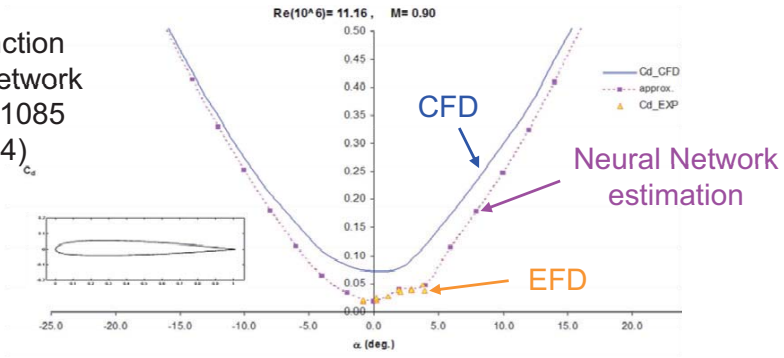
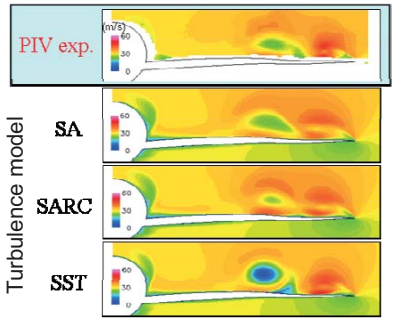
EFD/CFD Integration Techniques (2/3)

- Data fusion techniques
  - Predicting most probable aero. characteristics based on both EFD/CFD.

Ex: SFA (Sequential Function Approximation) Neural Network used to drag coeff. of SC1085 wing section (Meade 2004)



- EFD ⇒CFD
  - Optimum selection of turbulence model
  - Refinement of computational grid



PIV used for turbulence model selection
(velocity field around a cranked-arrow wing)

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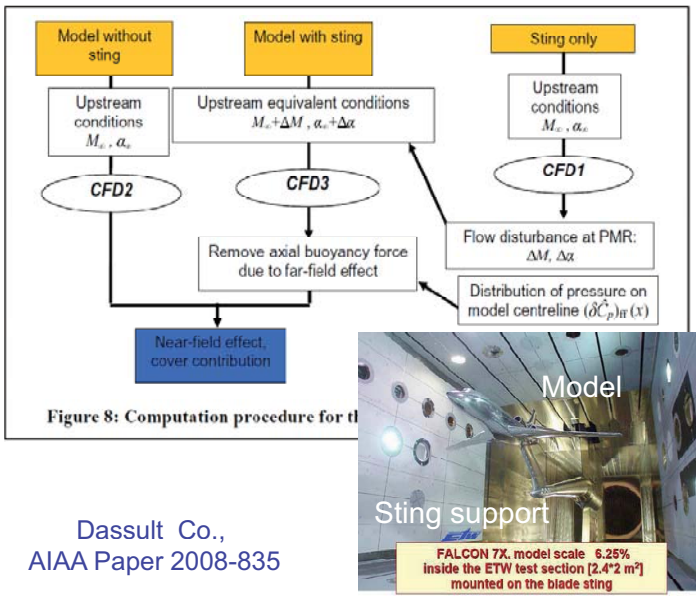
EFD/CFD Integration Techniques (3/3)

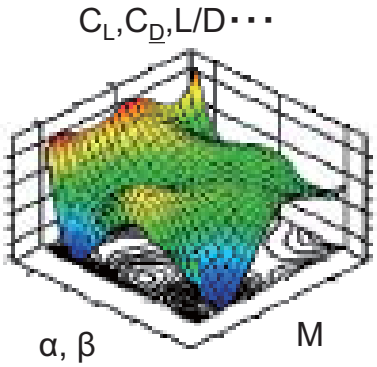
- CFD ⇒EFD
  - Accurate correction of wind tunnel wall/support interaction using CFD including model and WT.
  - Optimization of test model design and WT test planning based on pretest CFD.

Ex: Procedure of sting interaction correction



Dassult Co.,
AIAA Paper 2008-835

Ex: Utilization of response surface method in selection of WT test conditions



Summary

- JAXA has started the development of "Digital/Analog Hybrid Wind Tunnel" as a prototype realizing EFD/CFD integration. The initial system will be completed in 2011.
- Main technical development items:
  - ✓EFD/CFD integration techniques (comparison/visualization, correction of wall/support interaction, data fusion, etc.).
  - ✓Automatic grid generation and high-speed solver for Digital WT.
  - ✓Acceleration of image data reduction for aerodynamic measurement such as PIV.
- EFD/CFD integration technology is a key for increasing the value of the Hybrid Wind Tunnel. We will try to make rigorous collaborations with academia and industries for this purpose.

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Acknowledgements

Experimentalists :

S. Kuchi-Ishi, H. Kato, S. Koike, T. Hirotani, and M. Kohzai.
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CFD Researchers :

T. Aoyama, K. Murakami, A. Hashimoto, N. Fujita, and Y. Matsuo
Numerical Analysis Group, ARD, JAXA

Y. Yokokawa
Civil Transport Team, APG, JAXA

Ryoyu Systems Co., Ltd.

QUATRE-i Science

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Reducing Uncertainty in EFD and CFD Through Data/Model Fusion

JAXA Workshop

February 23, 2009

Andrew Meade
Rice University, Houston, Texas, USA

Acknowledgements

Postdocs: B. Zeldin, Michael Kokkolaras,

Graduate Students: Jose Navarrete, Wei Wang, and David Thomson

NASA Ames Rotorcraft Branch

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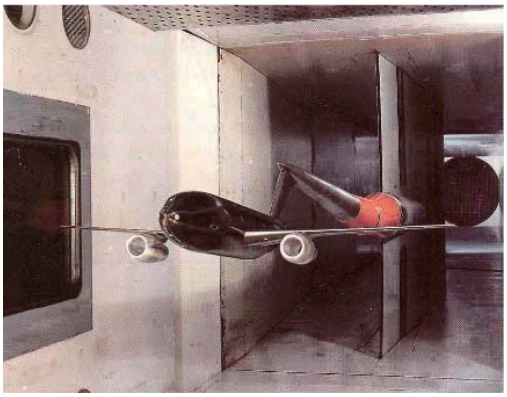
Background

As a graduate student working at NASA Ames Research Center I was well exposed to both the EFD and CFD communities.

At the time, they didn't always get along but we were on the same team.



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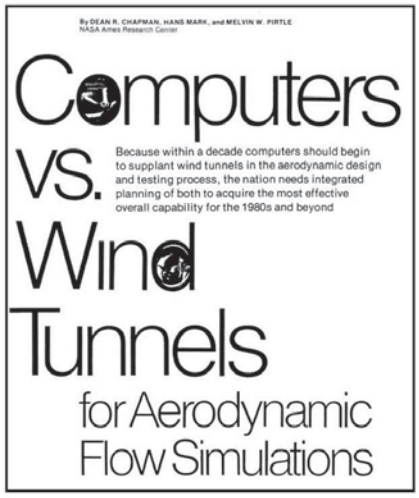
Background

Despite 30 years of advances in CFD, we now understand that it is nothing more than the third approach. CFD synergistically complements pure theory and experiments but it can never replace either of these other approaches.



Hans Mark, et. al. 1975

41. THE COMPUTER: RUIN OF SCIENCE AND THREAT TO MANKIND (1980/1982)

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1. Spatial Flight would have been Impossible without Computers 595
2. Spatial Flight would have been Impossible without the Classic Equations of Motion 596
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4. Computers have Harmed Science Already 601
5. Mathematics is the Science of Infinities. Computation is Essentially Finite 603
6. Computers Bring Power and the Abuses of Power. Advocates of Computing Seek to Destroy Mathematics 611
7. Computing Promotes Factual Fraud. It has Harmed Experimental and Applied Science in the Past and is Continuing to do so. By its Emphasis on Application of the Already Known, it can Delay Basic Discovery and thus Reduce the Field of Application in the Future 615
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Clifford Truesdell, 1984

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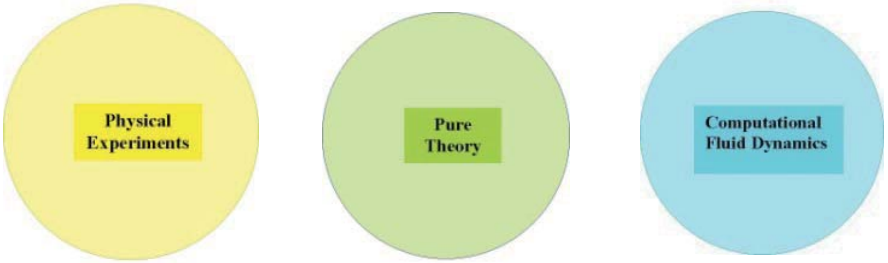
Background

The future advancement of fluid dynamics will rest upon a proper balance of all three methods.



Design of future aircraft and spacecraft will require even greater coupling between physical disciplines and better fidelity of their respective models (e.g., hypersonic aircraft)

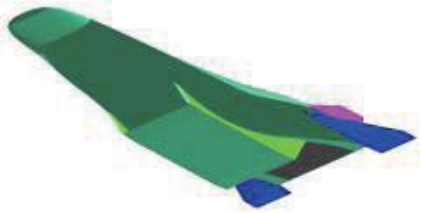


Figure: Notional NASA air breathing hypersonic aircraft design

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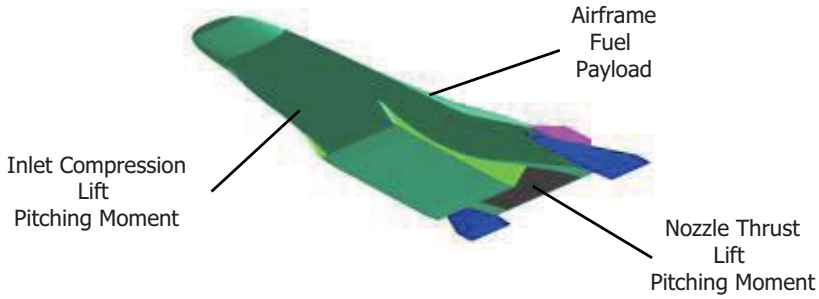
Background

Hypersonic Aircraft Example :

- Strong interactions between vehicle components
- Aerodynamics, propulsion, control, structure, tank, thermal protection, etc.
- Highly integrated engine and airframe
- Much of vehicle is engine inlet / nozzle
- Large propulsive lift and pitching moments – strong contributor to trim, stability & control
- Large Mach number and dynamic pressure variations in flight
- Severe aerodynamic heating
- Thermal protection must be integrated with structure
- High fuel mass fraction required - majority of volume accommodates fuel



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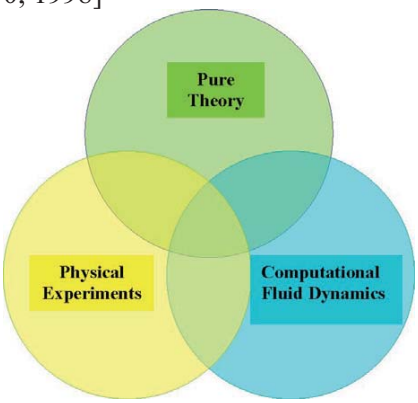
Background

We can develop a framework by which this synergy is accessible through the use of tools from scattered data approximation (machine learning tools) and Generalized Regularization (GR)

[A.N. Tikhonov and V.Y. Arsenin, *Solution of Ill - Posed Problems*, 1977]

[M. Ulbrich, TUM-M9810, 1998]



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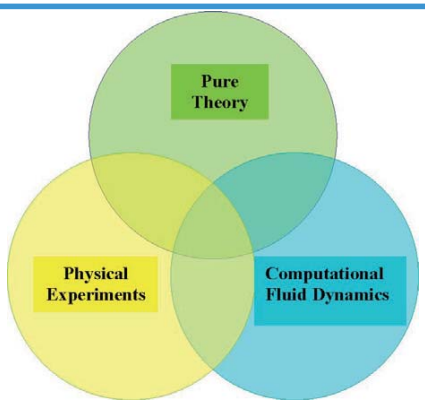
Background



Specifically, mathematical analysis of experimental data is treated as an ill-posed problem. Its regularization involves the introduction of additional information regarding the physical system.

We can then utilize a-priori mathematical models of physical systems at appropriate orders of fidelity for regularization. We can then investigate its potential in reducing uncertainty in EFD and CFD.

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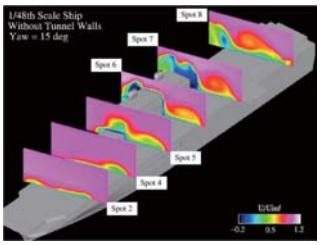
Motivation

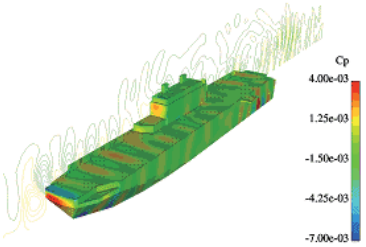
What are some of the potential applications of a fusion of mathematical models, computational methods, and experimental data?

- Filling in the blanks in experiments (including reducing uncertainty in EFD)
- Accelerating through test matrices (steering and predicting the amount of data needed)
- Accelerating CFD solutions using data (including reducing uncertainty in CFD)
- Noise filtering of data
- Knowledge discovery through parameter estimation

[Kurt Long, NASA Ames]



[Gloria Yamauchi, NASA Ames]



[Gary Sivak, Air Force Research Lab]

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Approach

To begin, define:

$d \equiv$ denotes the dimensionality of the approximation problem

$x_i \equiv \left(x_{1,i},\ldots,x_{d,i}\right) = d$ dimensional input

$\phi_k\left(x\right) \equiv k^{\text{th}}$ basis function

$c_k \equiv$ coefficients corresponding to the basis functions

$u(x) \equiv$ exact response of an unknown or underlying physical process

$f(x) \equiv$ observable output $\Rightarrow F\left(u\right) = f$

$\mu \equiv$ random noise of measurements at coordinate x_i

$f_e(x_i) \equiv$ experimental data points $= f(x_i) + \mu_i$

$u_a(x) \equiv$ approximation of $u(x) \Rightarrow u_a(x) = \sum_k \Phi_k\left(x\right) c_k$

The function $F\left(u_a\right) = f_a$ is designed to pass approximately through the experimental data points $f_e(x_i)$

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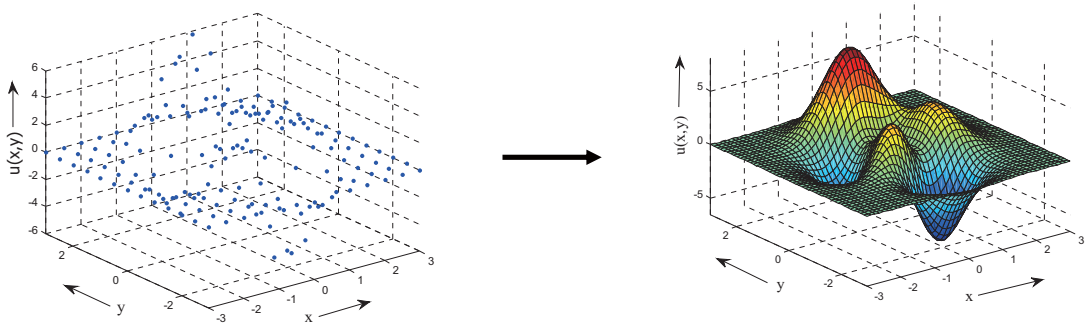
Approach

Basic Problem:

The construction of a response surface from the minimization of the standard square error,

$$\varepsilon = \sum_{i=1}^{s} \left[f_e(x_i) - F\left(u_a(x_i)\right) \right]^2$$

constitutes an ill-posed problem since u_a is nonunique and sensitive to the noise in data f_e.



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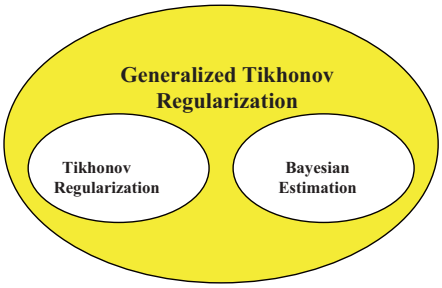
Approach

Solution:



The general idea in GTR is the minimization of

$$\varepsilon = A + \Lambda B$$

A is a scalar measure of the agreement between f_e and $F\left(u_a\right)$. In Bayesian terms A is related to *a posteriori* knowledge.

B is a stabilizing functional (i.e. regularizing operator) and is related to *a priori* information.

Λ is a positive scalar known as the regularization that controls the relevance of the *a posteriori* and *a priori* information to the approximation u_a.

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Approach

$$\varepsilon = A + \Lambda B$$

The regularizing operator, B, is classified as either quantitative or qualitative.

Can range from systems of time-dependent nonlinear partial differential equations, to statistical correlations, to heuristics.

Finding an approximate solution reduces to
(a) finding regularization operators B and
(b) determining the regularization parameter Λ from supplementary information pertaining to the problem, e.g., pertaining to the noise level in f_e.

B is not unique and depends on the type of physical process and the data type.

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Approach

In this context, the GTR formulation acts as a Swiss Army knife and gives us access to a number of popular methods in inverse problems.

Popular inverse problem methods include:

- Regularization by noise filtering
- Regularization by projection
- Conventional Tikhonov regularization $\Rightarrow A = \sum_{i=1}^{s} \left[f_e(x_i) - F\left(u_a(x_i)\right) \right]^2$ and B is a smoothing functional in variational form.
- Scattered data approximation for Response Surface Modeling (RSM) – includes support vector machines, radial basis functions, artificial neural networks
- Kalman Filter
- Bayesian Estimation

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Approach

Bayesian Estimation :

With $A = -2\log p(f_a \mid f_e)$, $B = -2\log p(f_a)$, and $\Lambda = 1$, then ε becomes the figure-of-merit function from Bayesian estimation theory.

Therefore, one can think of the GTR framework as a *deterministic* form of Bayesian estimation.

Kalman Filter :

Assume the measurement errors are Gaussian. The probability density functions act as if a differential operator is used to form B and operates on $u_0 - u_a$, where u_0 is the solution to a mathematical model of the time-dependent physical system of interest. The solution to the resulting Euler-Lagrange equation is $u_a = u_0 + u_{cor}$, where $u_{cor}(t_k) = F\left(\left(u_e(t_k) - u_0(t_k)\right), \tau\right)$. The basis functions for u_{cor} are the Green's function to a dynamic equation and τ is computed to minimize $\sum (u_0 - u_a)^2$ during the time marching.

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Approach

Back to Generalized Tikhonov Regularization

$$\Lambda \to \infty, \quad f_a(x) \to f_0(x) \qquad \text{and} \qquad \Lambda \to 0, \quad f_a(x) \to f_e(x)$$

One approach to determining the correct value for Λ is assuming the error is random, statistically independent and uniformly distributed in the interval $[-\tau, \tau]$. This will give,

$$\sum_{i=1}^{s}\left[f_e(x_i) - F(u_a(x_i))\right]^2 = E\left[\sum_{i=1}^{s}\left[f_e(x_i) - F(u_a(x_i))\right]^2\right] = E\left[\sum_{i=1}^{s}\mu_i^2\right] = s \cdot \mathrm{Var}(\mu) = s\frac{\tau^2}{3}$$

where $E[\square]$ denotes the operator of mathematical expectation.

Otherwise you can determine Λ such that Max $\left|f_e(x_i) - F(u_a(x_i))\right| \le \tau$

Note in both formulations, Λ is solved for iteratively and requires the solution of $f_a(x)$ within each iteration.

The direct solution of Λ is still an area of active research.

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Approach

Back to Generalized Tikhonov Regularization

Interesting Property

$$\Lambda \to \infty, \quad f_a(x) \to f_0(x) \qquad \text{and} \qquad \Lambda \to 0, \quad f_a(x) \to f_e(x)$$

One approach to determining the correct value for Λ is assuming the error is random, statistically independent and uniformly distributed in the interval $[-\tau, \ \tau]$. This will give,

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Note in both formulations, Λ is solved for iteratively and requires the solution of $f_a(x)$ within each iteration.

The direct solution of Λ is still an area of active research.

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Approach

GTR can use physical model in nonvariational form in place of B. A large class of mechanics problems can be described by the equations:

$$L\left[u_0(x)\right] = g(x), \quad x \in \Omega$$
$$\beta\left[u_0(x)\right] = 0, \qquad x \in \partial\Omega$$

Without a proxy, the minimum of $\varepsilon(u_a)$ satisfies

$$L\left[u_a(x)\right] = g(x) + 2\sum_{i=1}^{s}\left[\frac{u_e(x_i) - u_a(x_i)}{\Lambda}\right]\delta(x - x_i), \qquad x \in \Omega$$
$$B\left[u_a(x)\right] = 0, \qquad x \in \partial\Omega$$

Where $u_0(x)$ is the solution to the differential equation.

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Approach

The analytical solution to this modified mathematical model is

$$u_a(x) = u_0(x) + \sum_{i=1}^{s} G(x, x_i) c_i \quad \text{with} \quad c_i = \left\{ \left(\mathbf{G} + \frac{1}{2}\Lambda\mathbf{I} \right)^{-1} (\mathbf{u}_e - \mathbf{u}_0) \right\}_i$$

where $G(x, x_i)$ is the Green's function to $L[\square]$, $G(x_j, x_i) = \{\mathbf{G}\}_{j,i}$, and $\Lambda\mathbf{I}$ is a diagonal matrix.

Note that with $\Lambda \to 0$ we have $u_a(x_i) \to u_e(x_i)$ but the slope and curvature of $u_0(x)$ is used for interpolation. This means we can use the qualitative information from $u_0(x)$ and are not constrained by the quantitative properties.

In other words, additional information of *any* fidelity can be used.

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Approach

GTR possesses a number of useful properties. However:

- The Green's functions for practical models are usually unavailable. Is it possible to use existing numerical solutions in the literature for fusion?
- Is it possible to find a value for Λ that satisfies $s\frac{\tau^2}{3}$ without the trouble of solving for $u_a(x)$ explicitly?
- Rather than using a single value for Λ is it possible to use a distributed one?
- Is the full data set required to accomplish data-model fusion?
- Is it possible to do all of this with minimal user interaction?
- Can we accelerate through experiments with incomplete mathematical models or no model at all (Black-Box modeling)?
- Can we reduce uncertainty in EFD and CFD?

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Approach #1

$$\varepsilon = A + \Lambda B$$

We can also determine the minimum of $\varepsilon(u_a)$ through a conventional computational mechanics form using the Method of Weighted Residuals (MWR).

$$2\sum_{j=1}^{N}\left(\sum_{i=1}^{s}\phi_j(x_i)\psi_k(x_i)\right)c_j + \Lambda\left\langle\psi_k(x), L\left[u_a(x)\right]\right\rangle + \Lambda\ b\left\langle\psi_k(x),\ q\right\rangle =$$

$$2\sum_{i=1}^{s} f_e(x_i)\psi_k(x_i) + \Lambda\left\langle g, \psi_k(x)\right\rangle \quad \text{for} \quad k = 1,\ldots,N$$

with the constraint $\sum_{i=1}^{s}\left[f_e(x_i) - F\left(u_a(x_i)\right)\right]^2 \le s\frac{\tau^2}{3}$

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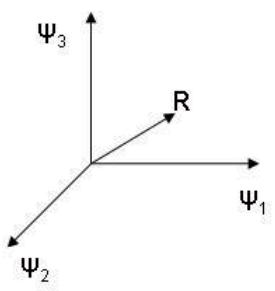
Approach #1

The MWR can be described as a numerical approximation method that solves for the coefficients c_i by setting the inner product of the weighted residual equation to zero:

$\left\langle R, \psi_k \right\rangle = 0, \quad k = 1,\ ...,\ s$

where $\mathrm{L}[u_a] - g = R$ and

$\psi_k \equiv$ weighting function



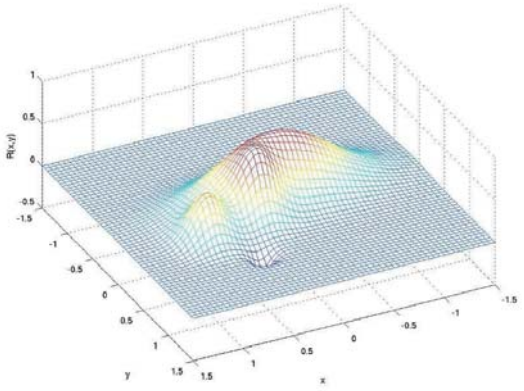


Figure: Distribution of the equation residual R.

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Approach #1

In this context, the MWR gives us access to many of the popular computational methods in a single framework.

Finite volume method: $\psi_k = \begin{cases} 1 \text{ in } \Omega_k \\ 0 \text{ outside } \Omega_k \end{cases}$

Collocation method: $\psi_k = \delta(x - x_k)$ where δ is the Dirac delta function

Least-squares method: $\psi_k = \dfrac{\partial R}{\partial c_k}$

Method of moments: $\psi_k = x^k$

Generalized Galerkin method: $\psi_k = F(\Phi_k) \Rightarrow$ finite elements

The form of the bases $\Phi_i(x)$ and the integration quadrature can also give us access to the finite difference and spectral methods.

Approach #1

So our numerical formulation can be written as the well-conditioned system

$$(\mathbf{H} + \Lambda\mathbf{M})\mathbf{c} = \mathbf{e} + \Lambda\mathbf{p} \quad \text{with} \quad \sum_{i=1}^{s}\left(f_e(x_i) - F(u_a(x_i))\right)^2 \le s\frac{\tau^2}{3}$$

H ≡ matrix containing the independent variable information of the measurement points
M ≡ conventional discretization matrix from computational mechanics
e ≡ vector representing the observational data
p ≡ forcing term vector of the *a priori* mathematical model with boundary conditions

- You can use the numerical method of your choice
- Λ acts as a penalty coefficient
- The data is embedded in the equation solution and acts an initial and/or boundary condition. **We have the potential to steer the CFD solution using EFD.**

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Approach #1

So our numerical formulation can be written as the well-conditioned system

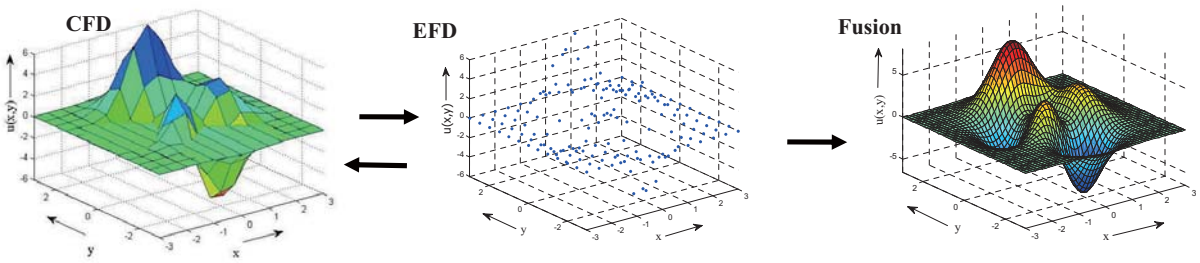
$$(\mathbf{H}+\Lambda\mathbf{M})\mathbf{c}=\mathbf{e}+\Lambda\mathbf{p} \quad \text{with} \quad \sum_{i=1}^{s}\left(f_e(x_i)-F(u_a(x_i))\right)^2 \le s\frac{\tau^2}{3}$$

CFD:

- We control the approximation method and its discretization.
- We use Λ to balance cost and fidelity of the *a priori* model against the cost of the experimental data in the approximation.

EFD:

- We control the quality and distribution of the experimental data - DoE.
- We balance the cost of the experimental data against the *a priori* model in the approximation.



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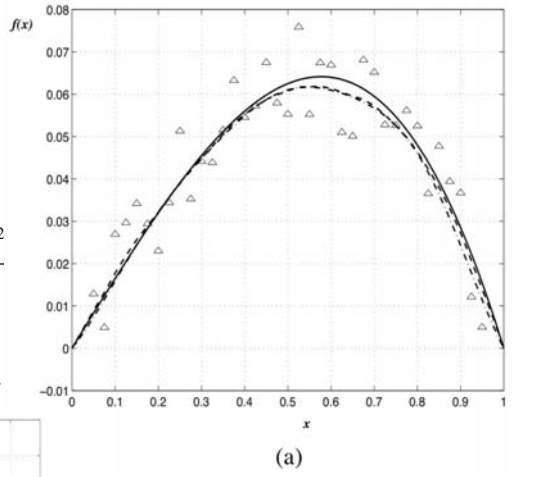
Approach #1 Results

Differential Equation Fused with Empirical Data
[B. Zeldin and A. J. Meade, *AIAA J.*, **35** (11) (1997)]

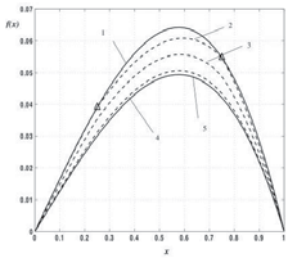
$$a\frac{d^2u}{dx^2}+x=0, \quad x\in(0,1), \quad u(0)=u(1)=0$$

$$(\mathbf{H}+\Lambda\mathbf{M})\mathbf{c}=\mathbf{e}+\Lambda\mathbf{p} \quad \text{with} \quad \sum_{i=1}^{s}\left(u_e(x_i)-u_a(x_i)\right)^2 \le s\frac{\tau^2}{3}$$

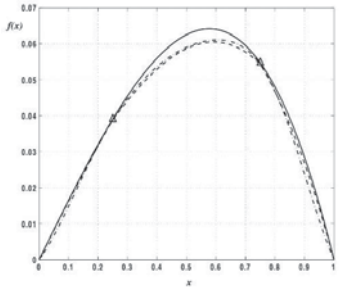
$a=1.0$ for $u(x)$ and $a=1.3$ for $u_0(x)$ with $|\mu_i| \le +0.014$.



Interpolation of data with noise.
Dashed curve – regularized analytical solution.
Dashed-dot curve – regularized ANN model with 7 RBFs



Response of regularized ANN system with insufficient data. 1 – response of the mechanical system,
2 – regularized response Λ = 0,
3 – regularized response Λ = 0.3,
4 – regularized response Λ = 3.0,
5 –response of a-priori mathematical model



Interpolation with insufficient data

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Approach #1 Results

The earliest and most common application of data/physical model fusion is in the dynamic modeling of weather.

Recognition by V. Bjerknes in 1904 that weather forecasting is fundamentally an initial-value problem and basic system of equations already known

- L. F. Richardson's (1922) attempt at practical Numerical Weather Prediction
- Late 1940s: First successful dynamical-numerical forecast made by Charney et al.
- 1960s: Edward Lorenz shows the atmosphere is chaotic and its predictability limit is about two weeks
- 1980s: Kalman Filtering applied to meteorology

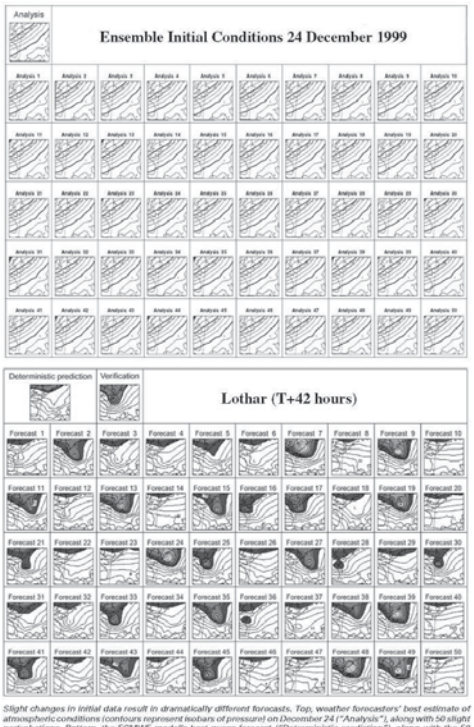
RICE University

Approach #1 Results

Kalman Filtering for Numerical Weather Modeling
[*SIAM News,* **36** (8) (1997)]

Kalman filter are provably optimal if the differential equations for the system are linear. Excellent for real-time linear computations.

SIAM 1997 article stated that the Kalman filter doesn't handle any serious nonlinearity and proposed remedies were just too complicated. This resulted in the modern Ensemble Kalman Filter.



Slight changes in initial data result in dramatically different forecasts. Top, weather forecasters' best estimate of atmospheric conditions (contours represent isobars of pressure) on December 24 ("Analysis"), along with 50 slight perturbations. Bottom, the ECMWF model's best-guess forecast ("Deterministic prediction"), along with the 50 ensemble members and a map of the conditions actually observed ("Verification"), 42 hours later; shading indicates low pressure. Ensemble methods, as results like these show, can detect in advance the possibility of weather that differs markedly from the best-guess forecast. Courtesy of the European Center for Medium-Range Weather Forecasts.

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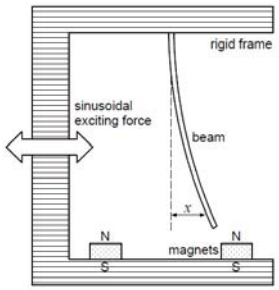
Approach #1 Results

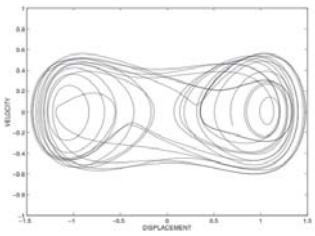
The Inhomogenous Duffing's Equation Merged with Empirical Data

[A. J. Meade and R. Moreno, *Intl. Journal of Smart Engineering System Design,* 1 (1998)]

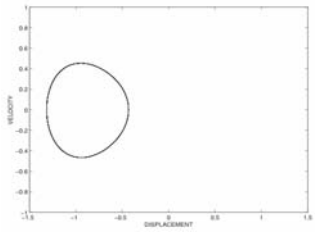
$$\frac{d^2x}{dt^2} + 2\mu\frac{dx}{dt} - \frac{1}{2}\left(x - x^3\right) = F_0\cos\left(\omega t\right)$$

$$\left(\mathbf{H} + \Lambda\mathbf{M}\right)\mathbf{c} = \mathbf{e} + \Lambda\mathbf{p} \quad \text{with} \quad \sum_{i=1}^{s}\left(\frac{dx_e}{dt}\left(t_i\right) - \frac{dx_a}{dt}\left(t_i\right)\right)^2 \le s\frac{\tau^2}{3}$$

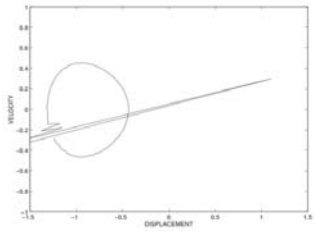




Chaotic phase space trajectory of the a-priori model for omega = 0.86



Desired nonchaotic trajectory.



Response of the model empirical merging.

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Approach #1 Results

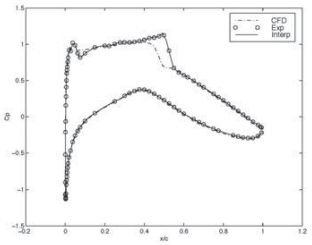
CFD Code Merged with Empirical Data

[W. Wang, M.S. Thesis, August 1998)]

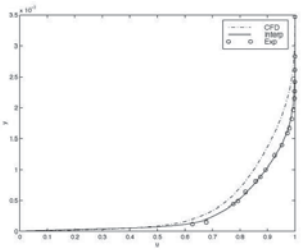
We have also had success with this formulation using a Thin-Layer Navier-Stokes solver in finite difference form fused with experimental surface pressure and boundary layer profile.

$$\left(\mathbf{H} + \Lambda\mathbf{M}\right)\mathbf{c} = \mathbf{e} + \Lambda\mathbf{p} \quad \text{with data as the BCs}$$

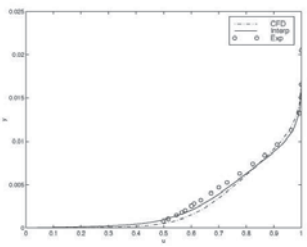
Case A	C_L	*error*
Experiment	-.1210	
CFD	-.0991	18.1%
Fused	-.1215	0.39%



Comparison of Pressure Coefficient Distribution for the RAE 2822 Airfoil at $M_\infty = 0.725$, $\alpha_{num} = 2.10$, $Re = 6.5 \times 10^6$



Comparison of Velocity Profile for the RAE 2822 Airfoil at $M_\infty = 0.676$, $\alpha_{num} = -2.30$, $Re = 5.7 \times 10^6$, $x = 0.179$



Comparison of Velocity Profile for the RAE 2822 Airfoil at $M_\infty = 0.676$, $\alpha_{num} = -2.30$, $Re = 5.7 \times 10^6$, $x = 0.90$ where no experimental data are used for fusing, but exist

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Approach #2

GTR questions:

- The Green's functions for practical models are usually unavailable. Is it possible to use existing numerical solutions in the literature for fusion?
- Is it possible to find a value for Λ that satisfies $s\frac{\tau^2}{3}$ without the trouble of solving for $u_a(x)$ explicitly?

- Rather than using a single value for Λ is it possible to use a distributed one?
- Is the full data set required to accomplish data-model fusion?
- Is it possible to do all of this with minimal user interaction?
- Can we accelerate through experiments with incomplete mathematical models or no model at all $\left(\text{Black-Box modeling}\right)$?
- Can we reduce uncertainty in EFD and CFD?

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Approach #2

An alternative method has been developed in hope of addressing the remaining concerns.

Starting with a straightforward reformulation using the solution to a numerical model, $u_{CFD}(x),$ from the literature

$$L\left[u_a(x)-u_{CFD}(x)\right]=0+2\sum_{i=1}^{s}\left[\frac{u_e(x_i)-u_a(x_i)}{\Lambda_i}\right]\delta\left(x-x_i\right), \qquad x\in\Omega$$
$$B\left[u_a(x)-u_{CFD}(x)\right]=0, \qquad x\in\partial\Omega$$

where $L[\square]$ and $B[\square]$ are now *linear* operators.

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Approach #2

If we define $e(x) \equiv u_e(x) - u_{CFD}(x)$

and use $G(x, x_i) = \phi_i(x)$,

then our solution to this modified form is

$$\sum_{i=1}^{N} \phi_i(x) c_i = u_a(x) - u_{CFD}(x) \quad u(x) - u_{CFD}(x) = e(x) - \mu(x)$$

This indicates that we need an approximation technique that can also address $\mu(x)$.

We will construct a *scattered data approximation* (i.e. response surface method) from the data $\{e(x_1),\ e(x_2),\ \ldots,\ e(x_s)\}$ and build to a tolerance τ equal to the maximum estimated measurement error $(\max |\mu_i| \leq \tau)$.

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Approach #2

These scattered data approximation techniques include:

- Kriging method (trouble with over 20 inputs and over 1000 data sets)
- Artificial neural networks, specifically radial basis function networks (RBFN), generalized regression neural networks (GRNN), and support vector machines (SVM).
- Greedy algorithms. This includes algorithms like Proper Orthogonal Decomposition (POD). We have developed our own greedy algorithm we call Sequential Function Approximation (SFA).

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Approach #2

Our SFA algorithm is a variation of Orr's Forward Selection training method and Platt's Resource Allocating network from machine learning that seeks to improve the computational efficiency through the MWR.

For convenience, we use the Gaussian radial basis function since it is unaffected by the dimensions d.

We set

$$\phi(x,\sigma_n,x_n)=\exp\left(\frac{-(x-x_n)\square(x-x_n)}{\sigma_n^{\,2}}\right) \quad \text{so then}$$

$$\begin{aligned} R_n(x,\sigma_n,x_n) &= u(x)-u_a^{(n)}(x)=u(x)-u_a^{(n-1)}(x)-c_n\phi(x,\sigma_n,x_n) \\ &= R_{n-1}-c_n\phi_n \end{aligned}$$

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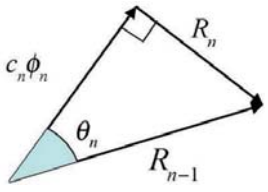
Approach #2

The objective is to determine c_n, σ_n, and x_n that minimize the residual R_n. Through the MWR we can reformulate the residual equation as a minimization problem,

$$\langle R_n,R_n\rangle=\langle R_{n-1},R_{n-1}\rangle-2c_n\langle R_{n-1},\phi_n\rangle+c_n^2\langle\phi_n,\phi_n\rangle \quad \text{which for an optimum } c_n;\ c_n=\frac{\langle R_{n-1},\phi_n\rangle}{\langle\phi_n,\phi_n\rangle}$$

$$\text{becomes} \Rightarrow \quad \frac{\langle R_n,R_n\rangle}{\langle R_{n-1},R_{n-1}\rangle}=1-\frac{\langle R_{n-1},\phi_n\rangle^2}{\langle\phi_n,\phi_n\rangle\langle R_{n-1},R_{n-1}\rangle} \quad \text{or} \quad \|R_n\|_2=\|R_{n-1}\|_2\sin\theta_n$$

where θ_n is the angle between R_{n-1} and ϕ_n. So this formulation should give $\|R_n\|_2<\|R_{n-1}\|_2$ as long as $\theta_n\neq\frac{\pi}{2}$.



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Approach #2

This formulation has characteristics similar to Proper Orthogonal Decompositon (POD), empirical basis function method, and the Krylov method.

We've used the SFA algorithm successfully with differential equations and conventional finite element basis functions in the mesh-free solution of differential equations.

We plan on using this mesh-free approach to determine whether or not CFD solutions can be steered by EFD results during calculations.

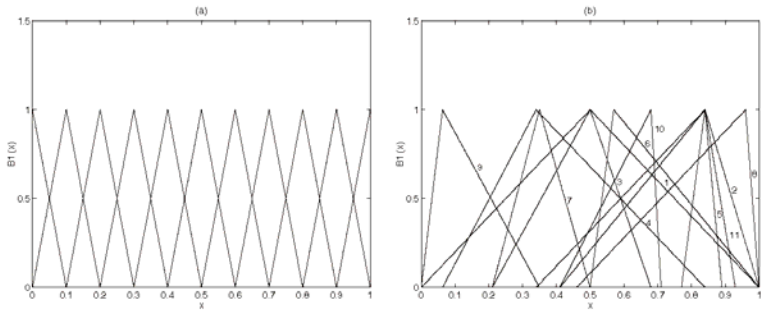

Figure 4.2 Basis functions distributions for the one-dimensional Poisson problem: (a) standard uniform and (b) optimal.

Approach #2

[A. J. Meade et al., *Communications in Numerical Methods in Engineering*, **13** (1997)]

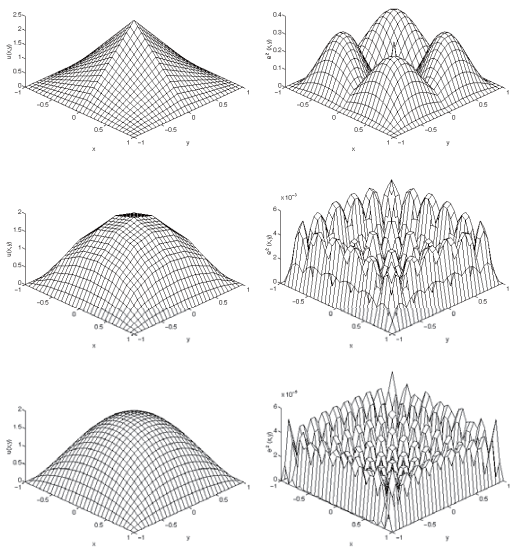

Figure 4.4 Two-dimensional Poisson's equation: (left) uniform grid finite element solutions and (right) associated squared error distributions for (top to bottom) $N = 9$, 49, and 441 bilinear Lagrangian shape functions.

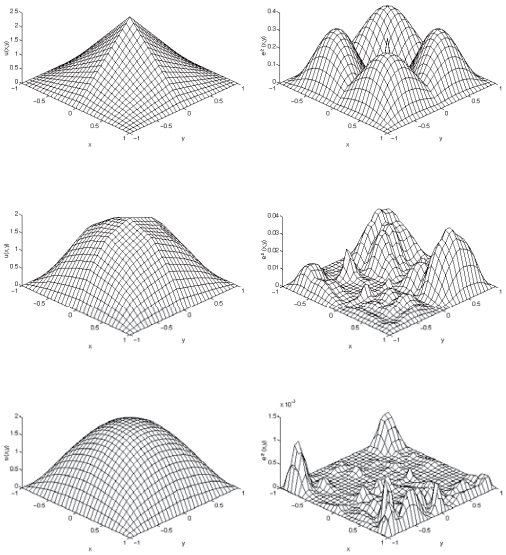

Figure 4.3 Two-dimensional Poisson's equation: (left) proposed method solutions and (right) associated squared error distributions for (top to bottom) $N = 1$, 10, and 100 optimal basis functions.

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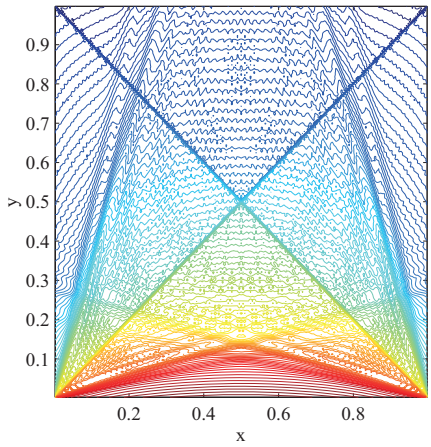
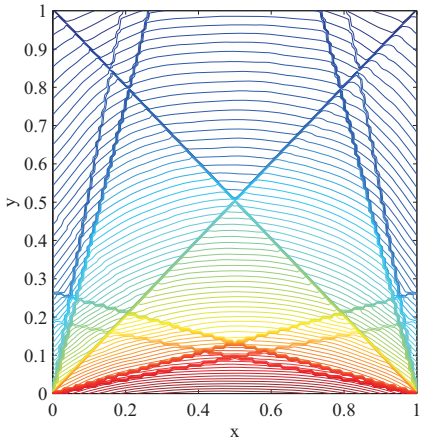
Approach #2

[D.L. Thomson et al. *International Journal of Thermal Sciences,* **40** (6) (2001)]

Discrete Ordinate Method (DOM) Thermal Radiation Problem



Non-dim. temp. approx. using 40401 finite volume bases



Non-dim. temp. approx. using 21 exp. bases by meshless method

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Approach #2

The solution for *discrete* data sets is the nonlinear minimization of

$$1-\frac{(\mathbf{R}_{n-1}\cdot\Phi_n)^2}{(\Phi_n\cdot\Phi_n)(\mathbf{R}_{n-1}\cdot\mathbf{R}_{n-1})} \quad \text{with} \quad c_n=\frac{(\mathbf{R}_{n-1}\cdot\Phi_n)}{(\Phi_n\cdot\Phi_n)},$$

The parameters c_n, σ_n, and x_n are solved for the n^{th} basis function sequentially.

The iterative process continues until either a pre-determined tolerance is reached

$\left(\text{i.e., } \max|\mathbf{R}_n| \le \tau \text{ or } \mathbf{R}_n\cdot\mathbf{R}_n \le s\frac{\tau}{3}\right)$ or $n = s$.

A conservative estimation of the convergence rate gives: $\mathbf{R}_n\cdot\mathbf{R}_n \le C_1\exp[-C_2 n]$

This approach has been used successfully with RBF in the approximation and analysis of high-dimensional scattered data problems.

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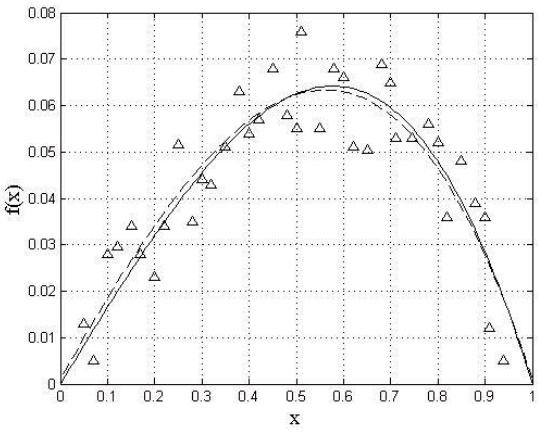
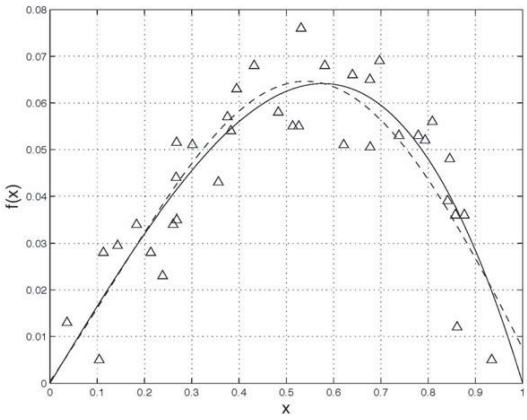
Approach #2 Results

Use of Scattered Data Approximation in Side-Stepping Λ

$$u(x)=\frac{\left(x^3+x\right)}{6},\quad u_0(x)=\frac{\left(x^3+x\right)}{6a},\quad u_a(x)=u_0(x)+\sum_{i=1}^{N}\phi_i(x)c_i$$



Interpolation of data with noise (±0.014) with a = 1.3.
Dashed curve – regularized ANN model with 1 RBF using SFA



Interpolation with noise (±0.05 and ±0.014) and a = 4.
Dashed curve – regularized ANN model with 1 RBF using SFA

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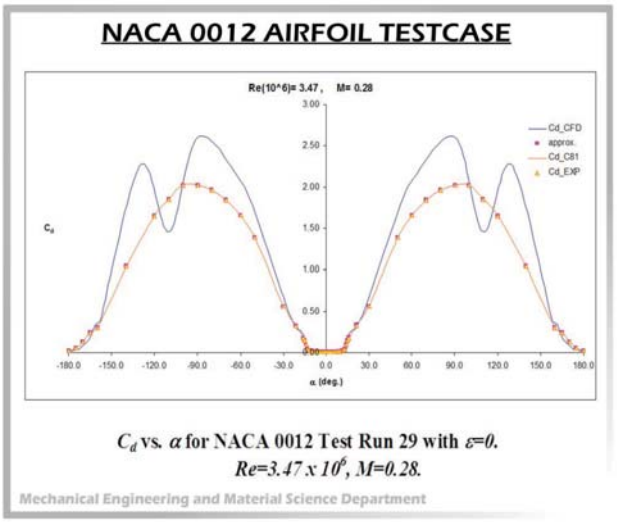
Approach #2 - Results

Regression / Fusion for An Airfoil Table

[J. Navarrete and A. J. Meade, AIAA 2004-0952]

We have used this approach to combine experimental airfoil coefficient data with numerical data in an effort to construct airfoil performance tables (C81 Tables) given limited data sets.



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Approach #2 - Results

Regression / Fusion of CFD Codes for Design

[D. Toal et al., *AIAA J.*, **46** 5 (2008)]

The use of scattered data approximation in side-stepping Λ has also been quite popular in computational aerospace design where it has been used in the construction of models by the fusion of multiple CFD solvers.

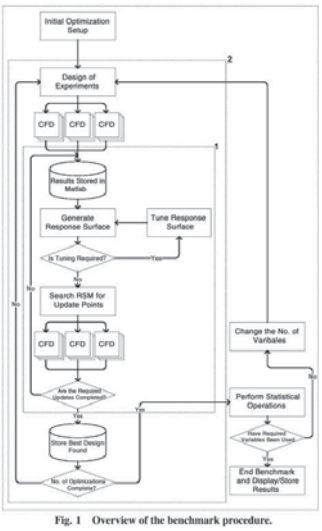

Fig. 1 Overview of the benchmark procedure.

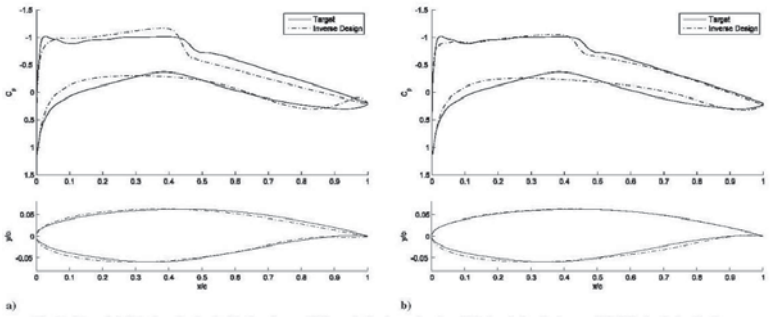

Fig. 7 Best airfoil design obtained with the nine-variable optimization using the a) 75-simulation budget and b) 150-simulation budget.

Approach #3

GTR questions:

- The Green's functions for practical models are usually unavailable. Is it possible to use existing numerical solutions in the literature for fusion?
- Is it possible to find a value for Λ that satisfies $s\frac{\tau^2}{3}$ without the trouble of solving for $u_a(x)$ explicitly?

- Rather than using a single value for Λ is it possible to use a distributed one?
- Is the full data set required to accomplish data-model fusion?
- Is it possible to do all of this with minimal user interaction?
- Can we accelerate through experiments with incomplete mathematical models or no model at all (Black-Box modeling)?
- Can we reduce uncertainty in EFD and CFD?

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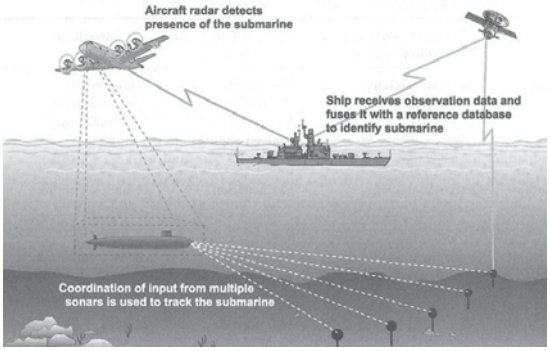
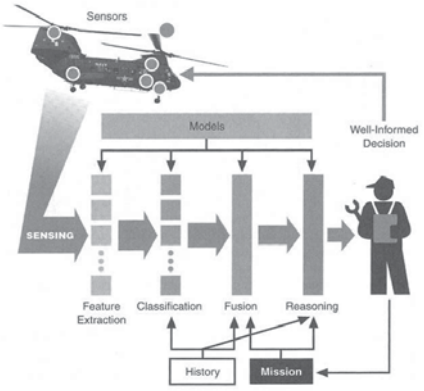
Approach #3

Bayesian estimation is by far the most popular technique in empirical information fusion (Black Box problems, i.e., data fusion without mathematical models). This approach has been used in everything from defense related decision codes to condition-based maintenance.

However, some practical difficulties do arise in a Bayesian framework in setting the *a priori* probabilities since noninformative priors can cause erroreous bias to further reasoning.





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Approach #3

I am a strong supporter of using scattered data approximation for aerospace problems since:

(a) it is a more straightforward numerical technique

(b) we already have an idea of the reliability of the sensors used in measurements

(c) setting the *a priori* probabilities are replaced with simply mapping the inputs to the known outputs.

(d) we showed in a previous paper that for a set basis function, this method should give us the best approximation.

We have applied our SFA algorithm to a Black-Box problem, a with proxy variable, in accelerating through an experiment.

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Approach #3 - Results

Identification / Classification of Naval Rotorcraft Recovery

[A. Srivastava et al. *Proc. of the 2007 Infotech@Aerospace Conference, 2007.*]

Physical experiments, especially flight tests, can be very expensive and tedious.

Design of launch/recovery envelope for a U.S. Navy helicopter requires:
4-5 days of ship-board flights
4 pilots, 2 aircrew, 4 test engineers, 5 maintenance personnel
Manuvering the ship to simulate various sea conditions
Hundreds of thousands of US$

Figures: HH-60H and U.S. Navy Amphibious Assault Ship

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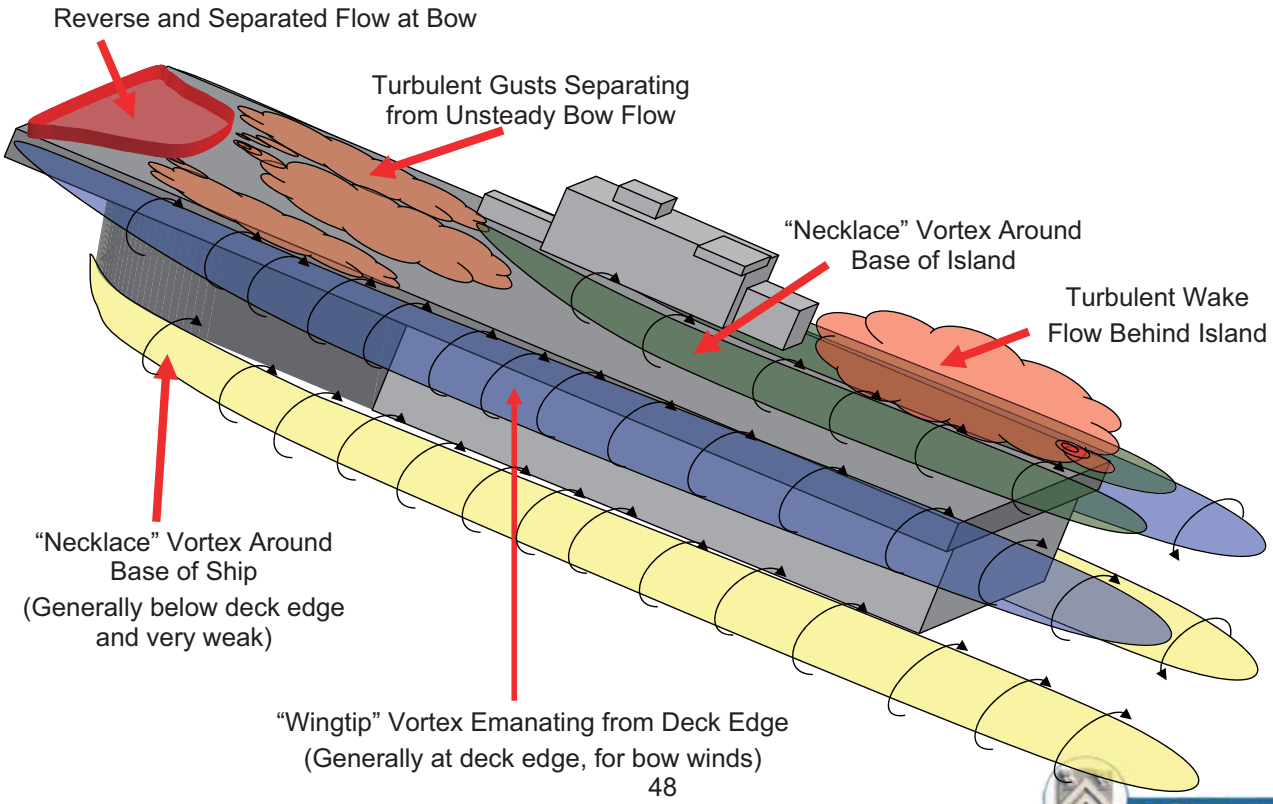
Approach #3 - Results



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Approach #3 - Results

Effort to replace the standard two-dimensional launch/recovery envelope. The SFA approach is used to construct a response surface that approximates the quality ratings of several HH-60H command pilots after recovery from Navy amphibious carriers.

369 data sets
13 dimensions
4 classes

PRS # Pilot Effort	Rating Description
1 Slight	No problems; minimal pilot effort required to conduct consistently safe shipboard evolutions under these conditions.
2 Moderate	Consistently safe shipboard evolutions possible under these conditions. These points define fleet limits recommended by NAWCAD Pax River.
3 Maximum	Evolutions successfully conducted only through maximum effort of experienced test pilots using proven test methods under controlled test conditions. Loss of aircraft or ship system likely to raise effort beyond capabilities of average fleet pilot.
4 Unsatisfactory	Pilot effort and/or controllability reach critical levels. Repeated safe evolutions by experienced test pilots are not probable, even under controlled test conditions.

Table: Pilot Rating Scale (PRS)

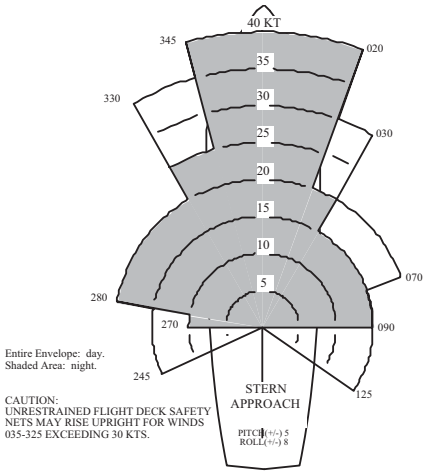

Figure: HH-60H Operational Recovery Envelope

Approach #3 - Results

This example was used to demonstrate that Black-Box fusion can be used for accelerating experiments and reducing uncertainty in experiments. This was thought to be a more rigorous test since there are no known models for the launch and recovery problem to fuse with the data and we are using a proxy variable.

We used DoE tools to select a small subset of the test matrix.
We imaged that the results from this first day of tests were then used to map the PRS to the inputs.

Input Index	Abbreviation	Definition (Units)
1	Ship Type	USN Ship Type: DD 967 (1), DDG 61 (2) DD 971 (3), DD976 (4)
2	WOD Spd	Wind Over Deck Speed. Relative wind speed (kts).
3	WOD Dir	Wind Over Deck Direction. Relative wind direction (degrees)
4	Long CG	Longitudinal CG station of helicopter. Length aft of datum (in).
5	Wfuel	Weight of fuel aboard helicopter (lb).
6	GW	Gross Weight of helicopter (lb).
7	Qavg	Average hover torque required during evolution (%).
8	Qmax	Maximum hover torque required during evolution (%).
9	Pitch	Pitch angle of ship during evolution (degrees)
10	Roll	Roll angle of ship during evolution (degrees)
11	OAT	Outside Air Temperature (degrees)
12	Hp	Pressure altitude (ft).
13	Hd	Density altitude (ft).

Table: Classification Model Inputs

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Approach #3 - Results

The resulting approximation was then used to predict the results of the next subset. Errors in predictions were used to update the PRS model. Because the SFA is a numerical technique with a known convergence rate, we can use this convergence rate to conservatively estimate how many more data points are necessary for the surrogate to reach some desired accuracy.

Applying sensitivity analysis to the PRS model we can also get an idea of which inputs are relevant to the test and eliminate those that have little effect on the PRS.

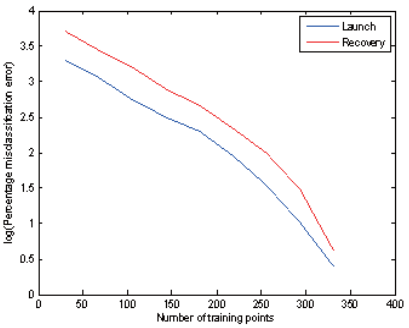

Figure: Decrease in error equivalent to the theoretical convergence rate.

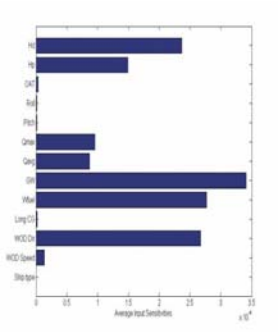

Figure: Average input sensitivities in the prediction of pilot ratings.

Approach #3 - Results

This convergence rate for black-box modeling also means that our prediction accuracy increases in a known manner, thereby reducing the uncertainty as more data is added to our approximation.

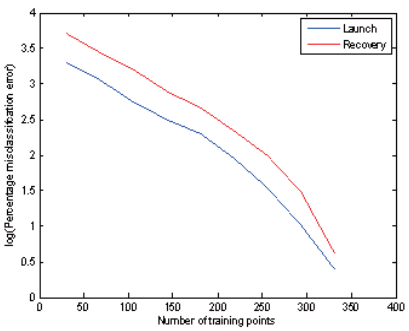

Figure: Decrease in error equivalent to the theoretical convergence rate.

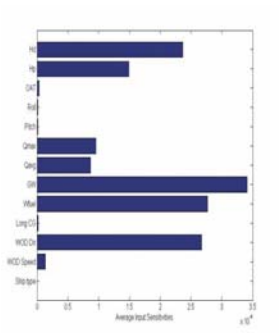

Figure: Average input sensitivities in the prediction of pilot ratings.

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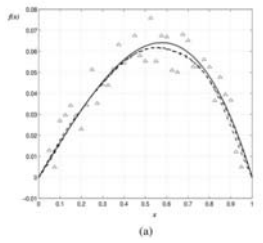
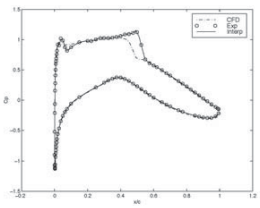
Conclusions & Future Work

It has been demonstrated that through the use of regularization, scattered data approximation, and meshless methods it is possible to seamlessly fuse mathematical models, computational methods, and experimental data. Possible benefits include:

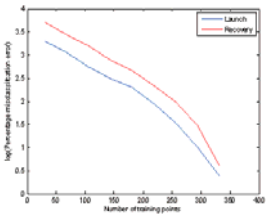
- Noise filtering of data (reducing the error bars)
- Filling in the blanks in experiments (including reducing uncertainty in EFD)
- Accelerating CFD solutions using data (including reducing uncertainty in CFD)
- Accelerating through test matrices (steering and predicting the amount of data needed)

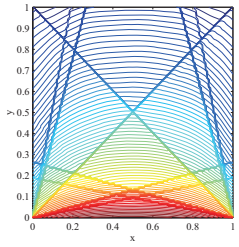


(a)



Comparison of Pressure Coefficient Distribution for the RAE 2822 Airfoil at $M_\infty = 0.725$, $\alpha_{trim} = 2.10$, $Re = 6.5 \times 10^6$





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Conclusions & Future Work

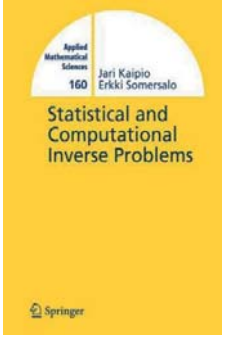
The Generalized Tikhonov Regularization framework shows promise as a way to merge theory, experimental observations, and computational fluid dynamics in a deterministic manner.

Further investigation of the method and the applications are required:

- Perform meshfree solution of $u_a(x)$ with the *solution* of $u_{CFD}(x)$ combined with $u_e(x_i)$. This would produce meshless and data-driven computational mechanics solvers.
- Investigate the method in designing better experiments and accelerating through them.
- Investigate the method with aerodynamic proxy data.

Suggested reading :
Keane & Nair

and Kapio & Somersalo :



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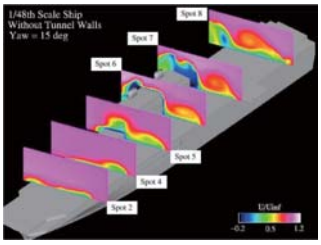
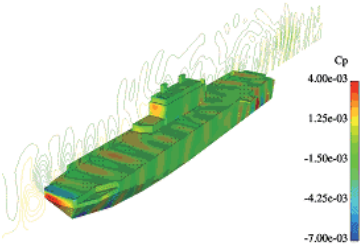
Conclusions & Future Work

I would like to see us as a community, using whatever tools become suitable, to routinely drive and merge experiments with various CFD solvers and have this become a regular part of our student's education and research thinking.

In addition to archiving our CFD results in journals, these models can then be used as international databases that can be further refined with advances in CFD and EFD. As a result, work does not have to be needlessly reproduced and uncertainty can be reduced in future experiments.





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Conclusions & Future Work

Questions?

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Validation and Minimizing CFD Uncertainty for Commercial Aircraft Applications – The Integration of EFD and CFD

Edward N. Tinoco
Boeing Commercial Airplanes
Seattle, Washington, USA

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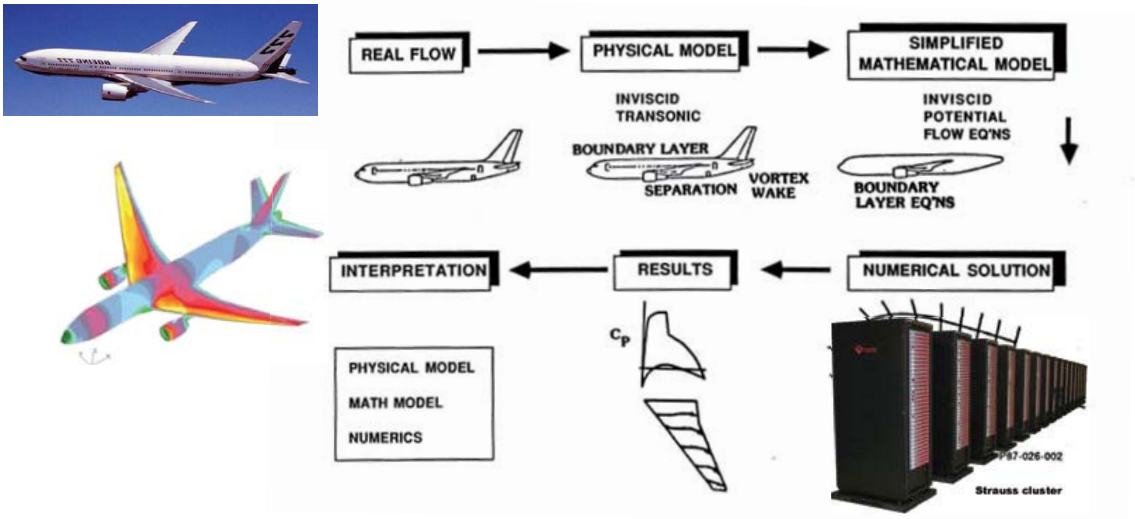
• **Scope: Validation experiences presented are limited to the application of Computational Fluid Dynamics (CFD) to high-speed (transonic) commercial transport vehicles**

Computational Fluid Dynamics



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Outline

- Scope: Validation experiences limited to high-speed (transonic) commercial transport vehicles
- Motivation
- Validation for an Intended Purpose
  - Codes - CFD
  - Knowing the test data - EFD
  - Adventures in validation
- Minimizing CFD Uncertainty
- Case Study – 3rd Drag Prediction Workshop
- Concluding Remarks

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Motivation

To get value out of CFD you must get CFD into the Product.

- CFD must get into the hands of the engineers responsible for the development of the product.

- CFD must be predictive
  - – Predictive results must be timely.
  - – Predictive results must be consistent

- Management must believe in the use of CFD.
  - – Makes economic sense.
  - – Usable by the engineers on the project.
  - – Confidence that both CFD and Users are validated.

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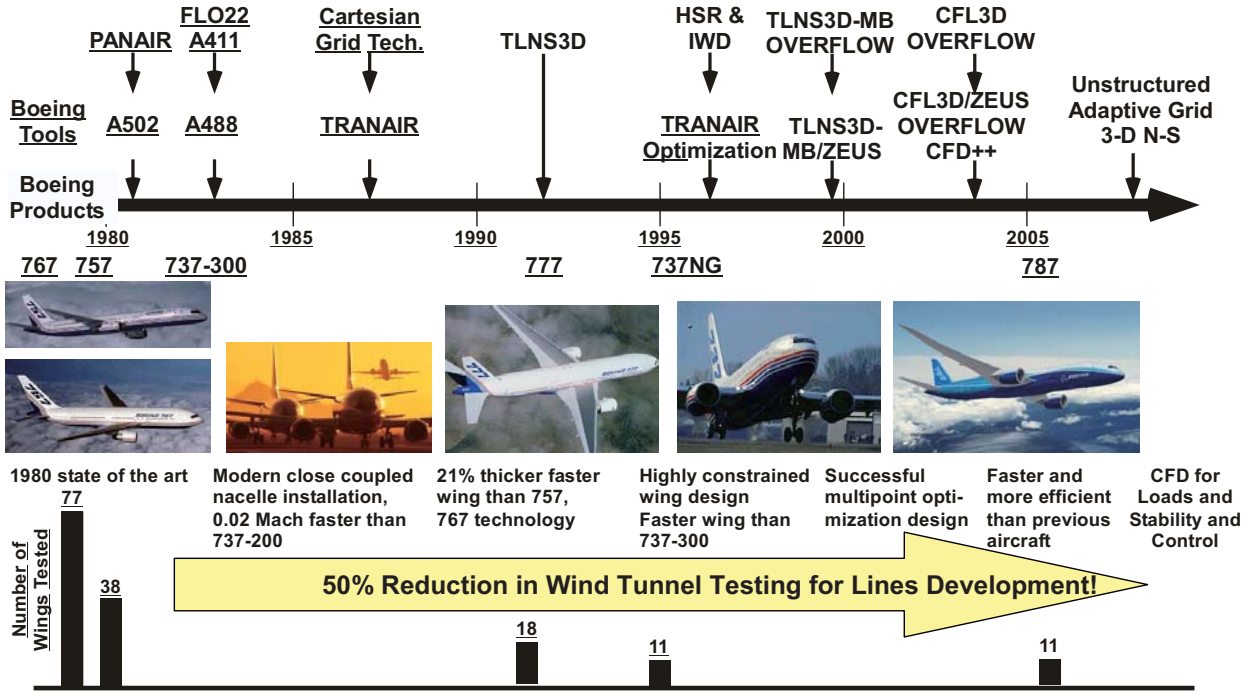
The Impact of CFD on Configuration Lines Development Wind Tunnel Testing



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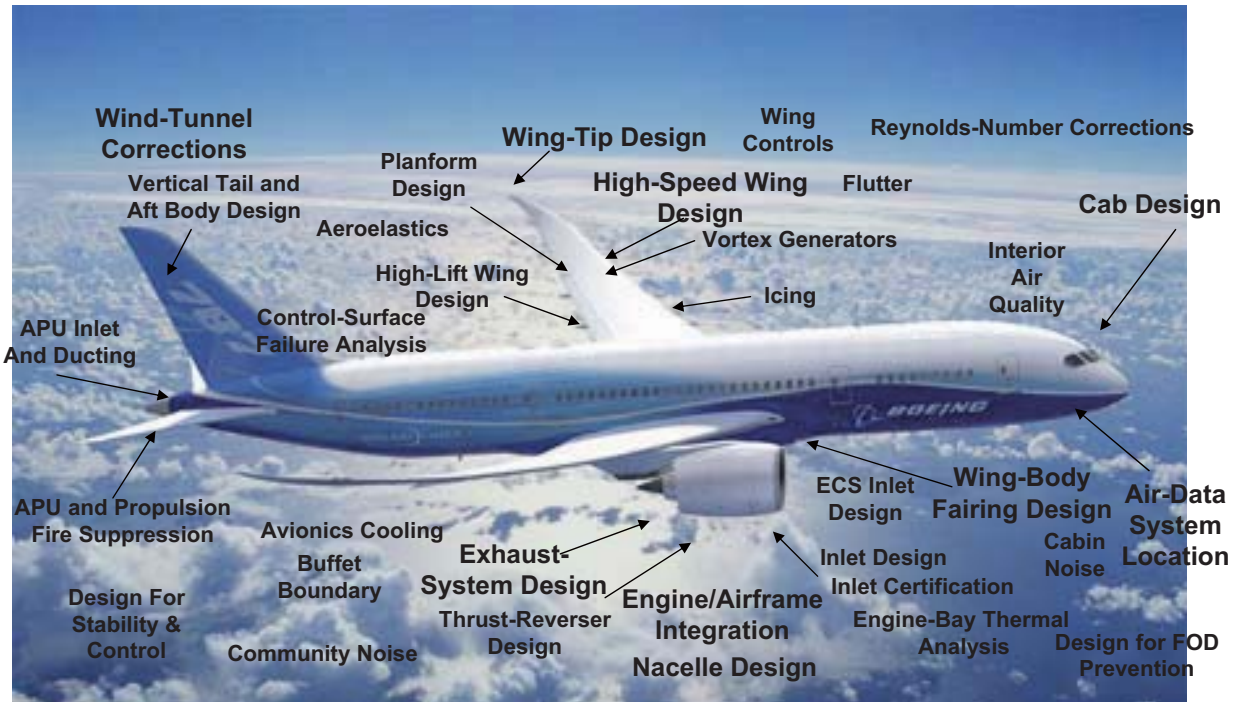
CFD Contributions to 787



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Use of CFD and therefore the Need for Validation has been driven by "Desperation"

- Not being able to meet high-speed drag design goals by traditional "cut & try" wing design in 1980's led to "inverse design" via pressure matching
  - Need - Validated accuracy of wing pressure distribution prediction
  - Used on 777 and Next-Generation 737

- Not being able to meet high-speed drag design goals by "inverse design" wing design on 4-engine airplane in 1990's led to "optimization" drag design
  - Need – Validated prediction accuracy of configuration drag increments due to small geometry perturbations
  - Used on Sonic Cruiser, 787, 747-8

- Increased market pressure to reduce airplane development cycle time
  - Need – Validation of prediction accuracy of CFD for Loads and S&C
  - Used on 787 and 747-8

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Verification, Validation, Calibration, and Certification?

From a recent update from the AIAA committee on Standards for computational fluid dynamics we see *verification and validation of CFD codes and calculations as the process of determining the level of confidence that can be placed in the resulting CFD data where:*

Verification: The process of determining that a model implementation accurately represents the developer's conceptual description of the model and the solution to the model.

Validation: The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.

These are necessary first steps leading to:

Validation for Intended Purpose

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Validation for Intended Purpose

- Instill “user confidence” that the “CFD processes” can deliver solutions that are “good enough”.
- “Good enough” depends on intended use and is in the eyes of the user.
- “Good enough” is frequently measured with respect to test data that has itself been deemed “good enough”
  - CFD should not exactly match test – both have different limitations
  - Matching data at 2 or 3 conditions is inadequate/misleading
  - Need trends over multiple conditions and configurations
- CFD code by itself can never be validated for an intended purpose
  - Too many variables – user accessible “knobs”
  - Grids – too much dependence
- “CFD process” from lofts, grid generation, solver, post-processing, etc. must be focus of establishing “user confidence” in being “good enough”

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Computational Methods
(addressed in this presentation)

TRANAIR

- Full Potential with directly coupled Boundary Layer
- Cartesian solution adaptive grid
- Drela lag-dissipation turbulence model
- Multi-point design/optimization

Navier-Stokes Codes

- CFL3D – Structured Multiblock Grid
- TLNS3D - Structured Multiblock Grid - Thin Layer
- OVERFLOW – Overset Grid

N-S Turbulence Models

- S-A Spalart-Allmaras
- Menter's k-w SST

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Knowing the Test Data

Neither wind tunnel nor flight test data can be considered an absolute against which to compare CFD for validation.

Flight Test Uncertainties

- Flight Conditions – Mach number, angle of attack, slideslip calibrations. Ability to hold conditions in flight.
- Forces – No direct measurements, inferred from flight characteristics, fuel burn.
- Pressures – limited in number, subject to significant instrumentation lag.
- Shape – Aircraft aeroelastics, control surface deflections.

Wind Tunnel Test Uncertainties

- Better control and measurement of flight conditions, forces, pressures, shape, etc. but:
  - Generally at much lower Reynolds number than full scale flight
  - Must be corrected for significant wall and mounting system effects to represent "free-air". Complete corrections not practical.
- Better statistical evaluation
  - Short term and long term repeats within a test entry
  - Test to test repeats
  - Tunnel to tunnel repeats

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Wind Tunnel Data Corrections

Clear tunnel flow conditions are subject to small variations in pressure and flow direction. The introduction of the wind tunnel model further disturbs these quantities away from "free-air".

- **Mach Number – Function of total and static pressure**
  - **– Centerline pressure vs. static measurement**
  - **– Static pressure change due to model presence – "Mach Blockage"**
- **Angle-of-Attack – A derived quantity – physical angle + corrections for:**
  - **– Flow angularity – "Up-flow"**
  - **– Lift interference – "δ_o" – Model to tunnel size, tunnel wall ventilation, Mach**
- **Drag – Measured force corrected for angle-of-attack, + corrections for:**
  - **– Clear tunnel buoyancy**
  - **– Solid blockage buoyancy**
  - **– Internal cavity pressures**
  - **– Normalized skin friction**
- **Tare and Interference – can effect all quantities, specific to model, tunnel, Mach number**

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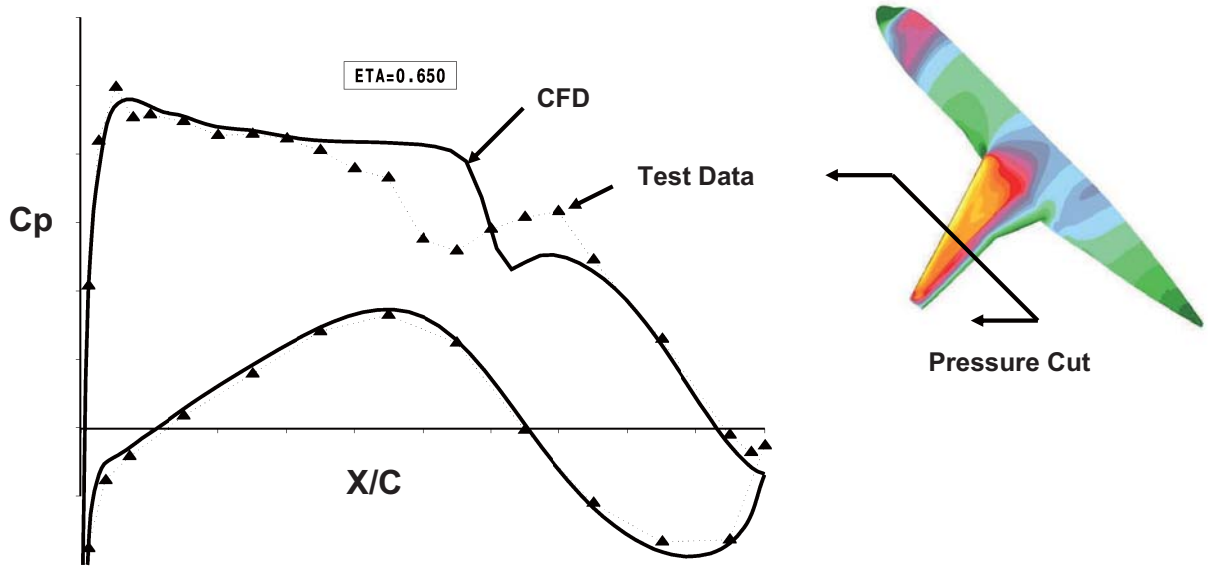
Poor Validation Choice

The CFD development team struggled for nearly a year trying to get better agreement with test data.



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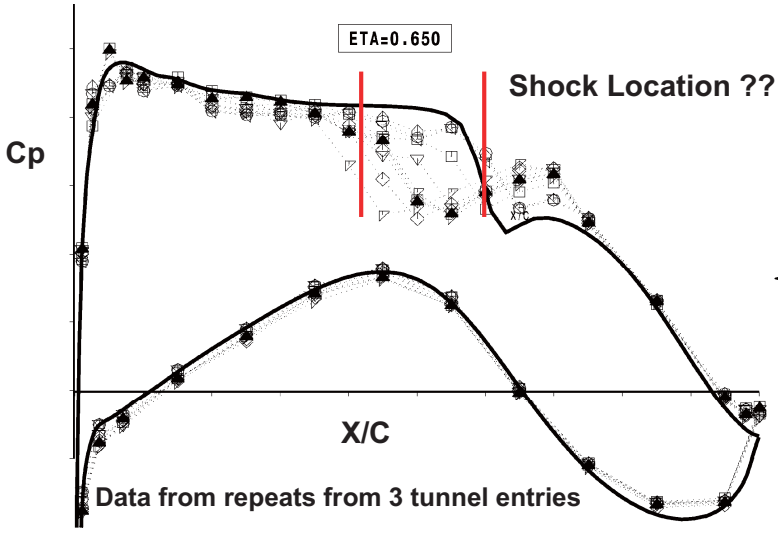
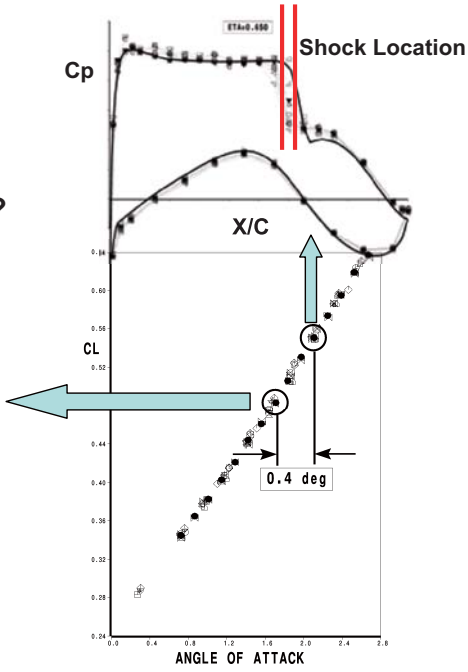
Poor Validation Choice

Extreme Sensitivity of Shock Location to Flow Conditions

Sensitivity of the shock location to exact Mach and angle of attack is very high at this condition - the correlation will be very poor.





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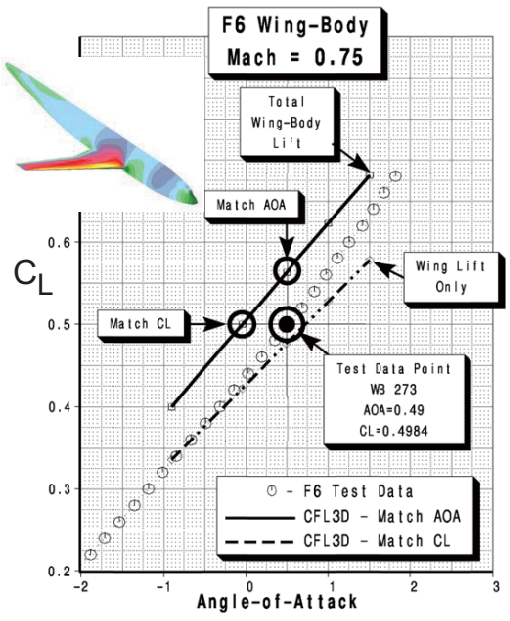
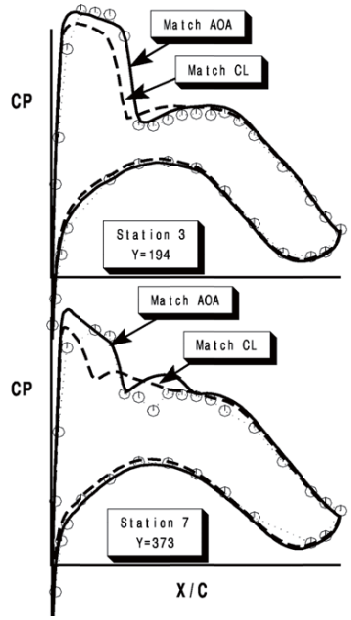
Inconsistency between forces and pressures

DLR F6 Wing-Body **Wing Cp's – Match α or CL?**





- **Apparent wing pressure agreement at given angle of attack raises question about lift force.**
- **Not enough information available to determine why**

From the 2nd AIAA Drag Prediction Workshop

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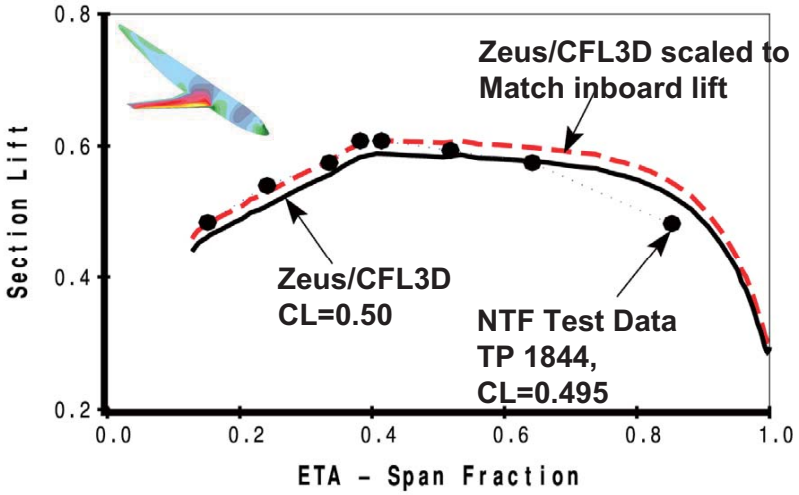
Inconsistency between forces and pressures

Probable cause – wrong wing twist in CFD model!



Increasing the nose down twist on the outboard part of the wing will result in a higher angle of attack when matching CL thereby better matching the wind tunnel force and pressure data.

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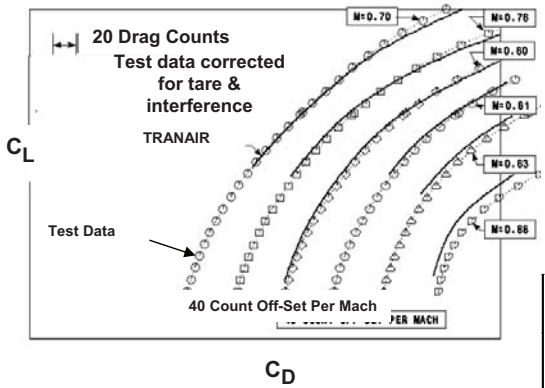
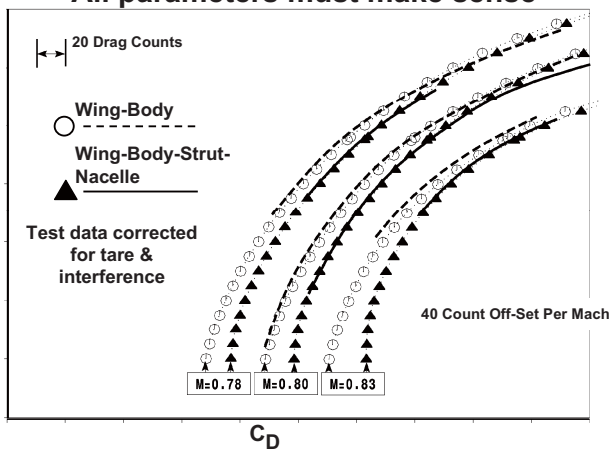
Validation for Drag



- A single drag tare added to all TRANAIR results
- Comparison made over a range of Mach and angle-of-attack
- Emphasis placed on incremental drag
- All parameters must make sense



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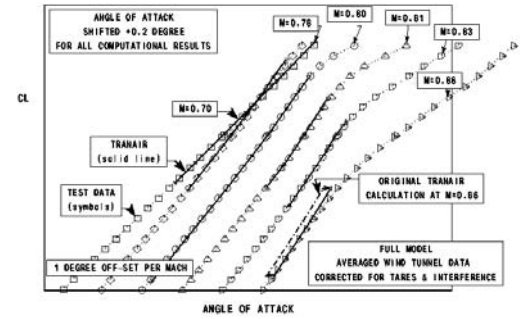
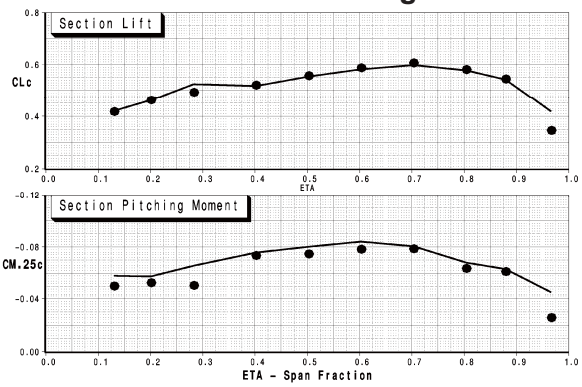
Validation Must Make Sense for all Parameters

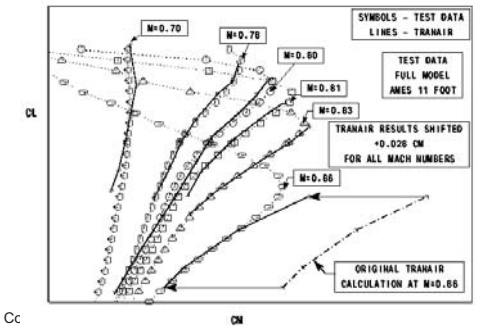
Total Lift



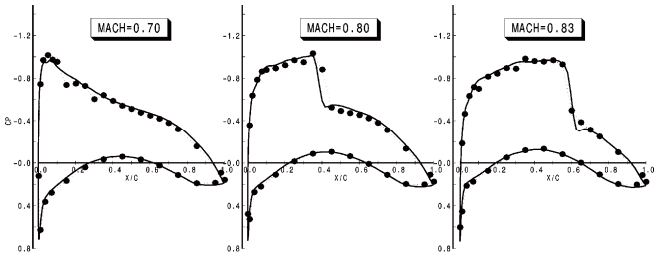
Section Lift and Pitching Moment



Total Pitching Moment



Pressure Distributions



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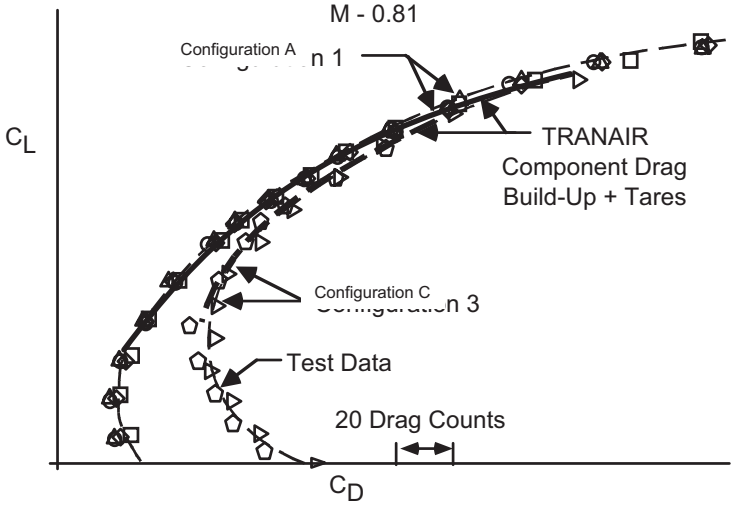
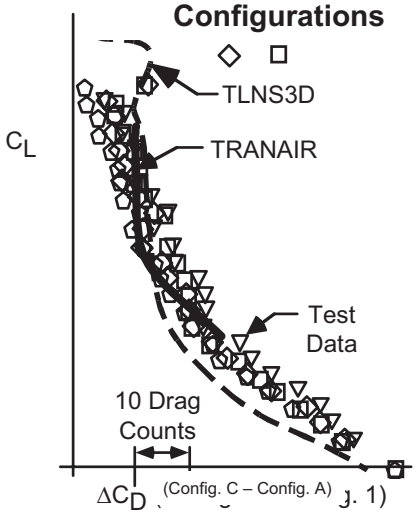
Code to Code, Code to Test Comparisons

- Validation with multiple code adds to confidence
- A single drag tare added to results from each code
- Different levels predicted but same incremental delta

Wing-Body Drag Polars



Incremental Drag between Configurations



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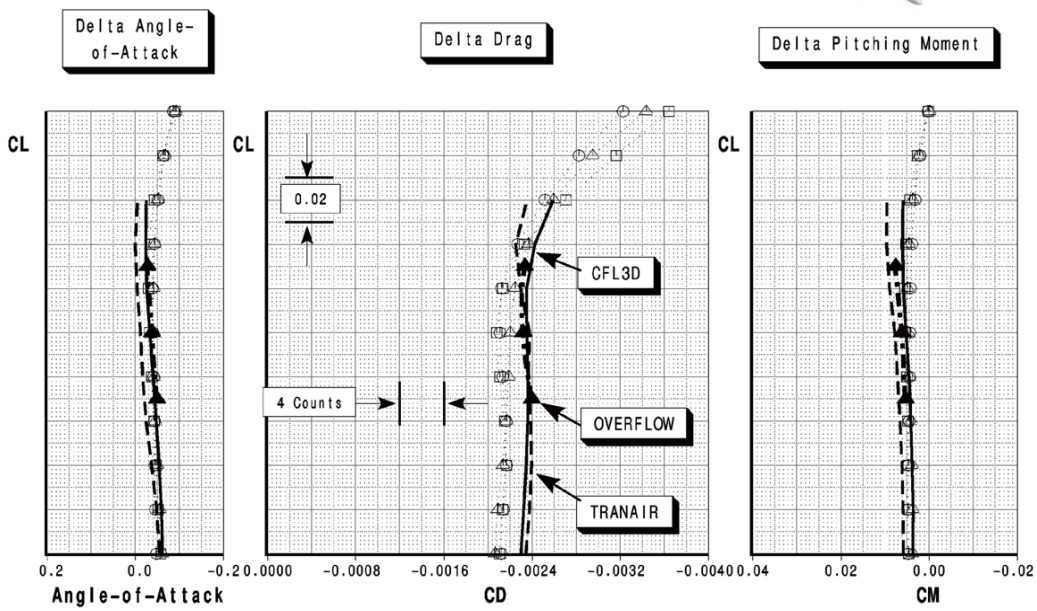
Code to Code, Code to Test Comparisons

- Validation with multiple code adds to confidence
- Consistent processes yield consistent results



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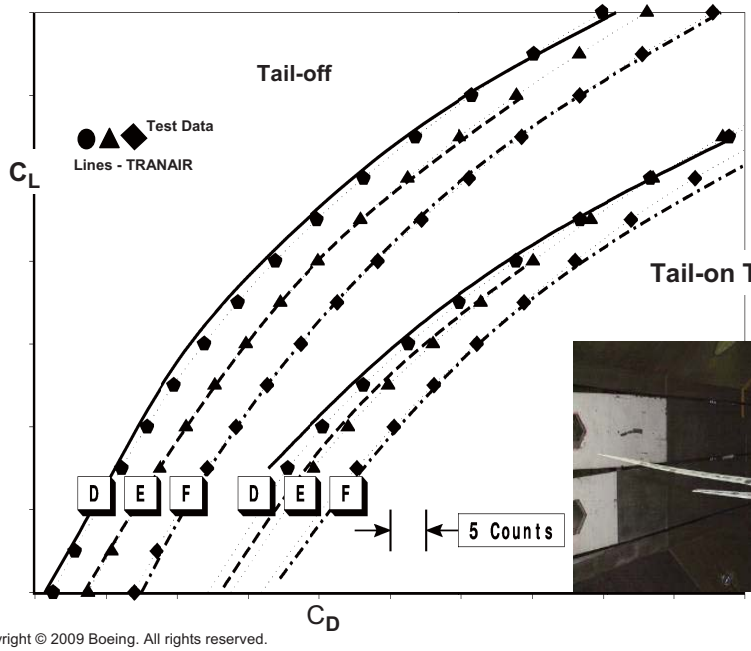
Consistency Builds Confidence in Validation

Predictive CFD – The bulk of these results were obtained pre-test!



- **Single drag tare added to all results**
- **Consistent processes yield consistent results**
- **Consistent results build confidence**

Tail-on Trimmed to C_M=0.

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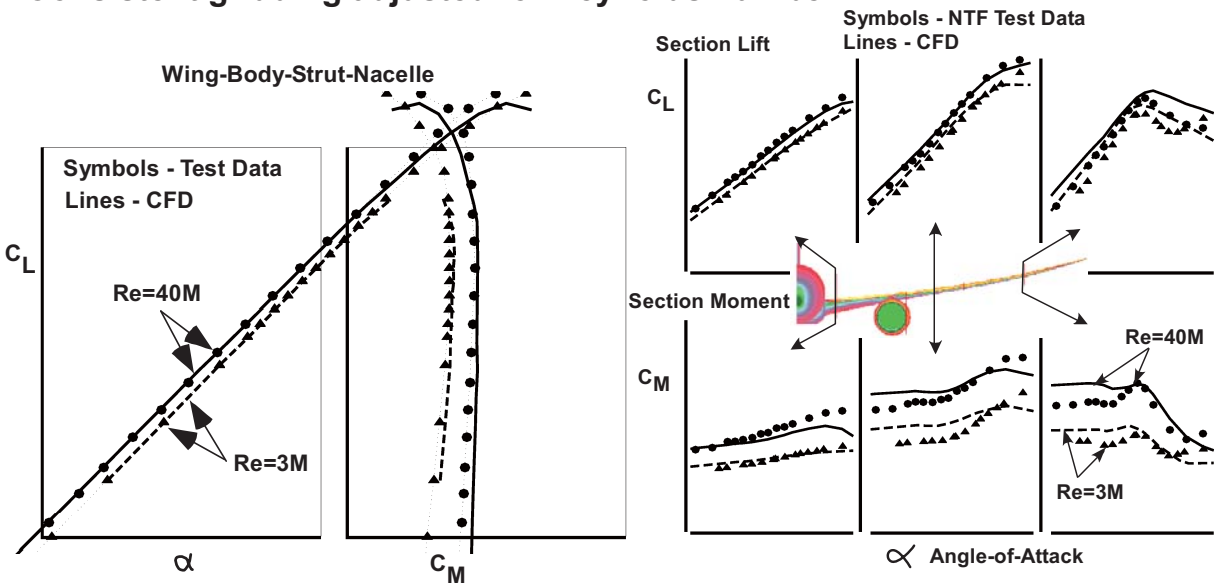
Reynolds Number Effects

- Use CFD to provide Reynolds number corrections to conventional wind tunnel data
- Consistent gridding adjusted for Reynolds number



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Single tare added to CFD results

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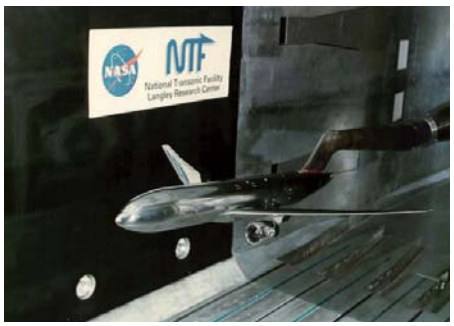
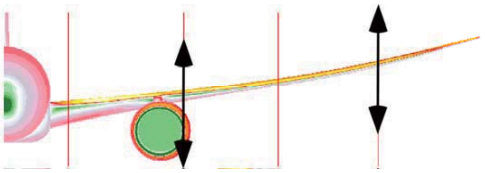
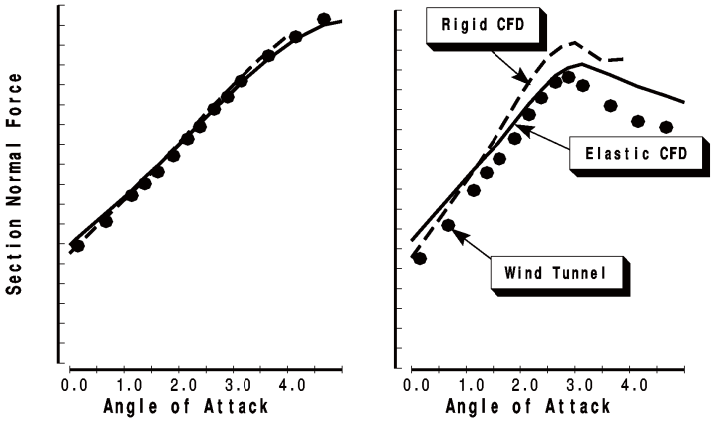
The Importance of Wing Tunnel Model Aeroelastics

- Accounting for wind tunnel aeroelastics adds confidence to CFD validation







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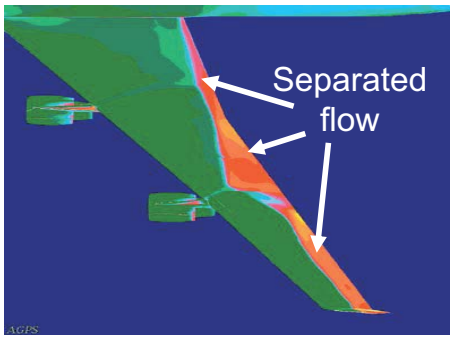
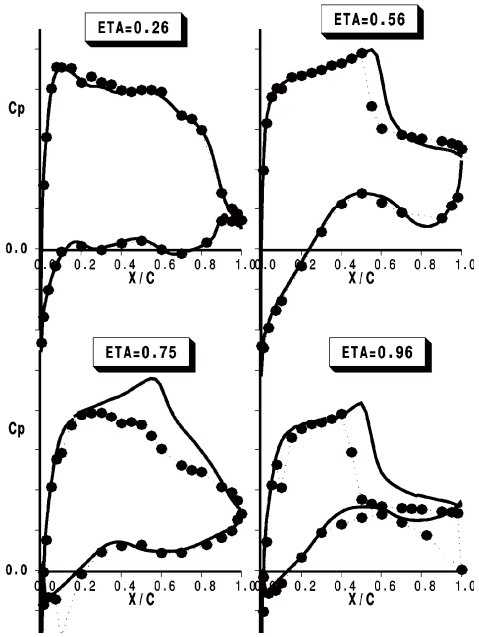
CFD at the Edges of the Envelope

- CFD Issues
  - Large regions of separated flow
  - Turbulence models
  - Need URANS or DES?
- Testing Issues
  - Close to Mach One
  - Model aeroelastics
  - Representative of "Free Air"?



Cp comparison at approximately 2.5g at Mach dive



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Outline

- Scope: Validation experiences limited to high-speed (transonic) commercial transport vehicles
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- Validation for an Intended Purpose
  - Codes
  - Knowing the test data
  - Adventures in validation
- Minimizing CFD Uncertainty
- Case Study – 3rd Drag Prediction Workshop
- Concluding Remarks

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Minimizing CFD Uncertainty - Stable, Packaged Software Solutions – not just codes.

Product Development engineers must be able to focus on on engineering processes and have little time for manipulating CFD "process", i.e. codes must be very user oriented.

- **Consistent, Repeatable Processes**
  - **Enables fast results, reduces variation.**
- **Integrated Stable, Packaged Software Solutions**
  - **Scripted Packages for "standard" configurations**
  - **Geometry, Grid/Paneling Generation**
  - **Solvers**
  - **Post-processing**
  - **Software Version Control**
- **Integrated Computing Resources**
  - **High-end Computing Resources**
  - **Mass Data Storage**
  - **Computing System Administration**

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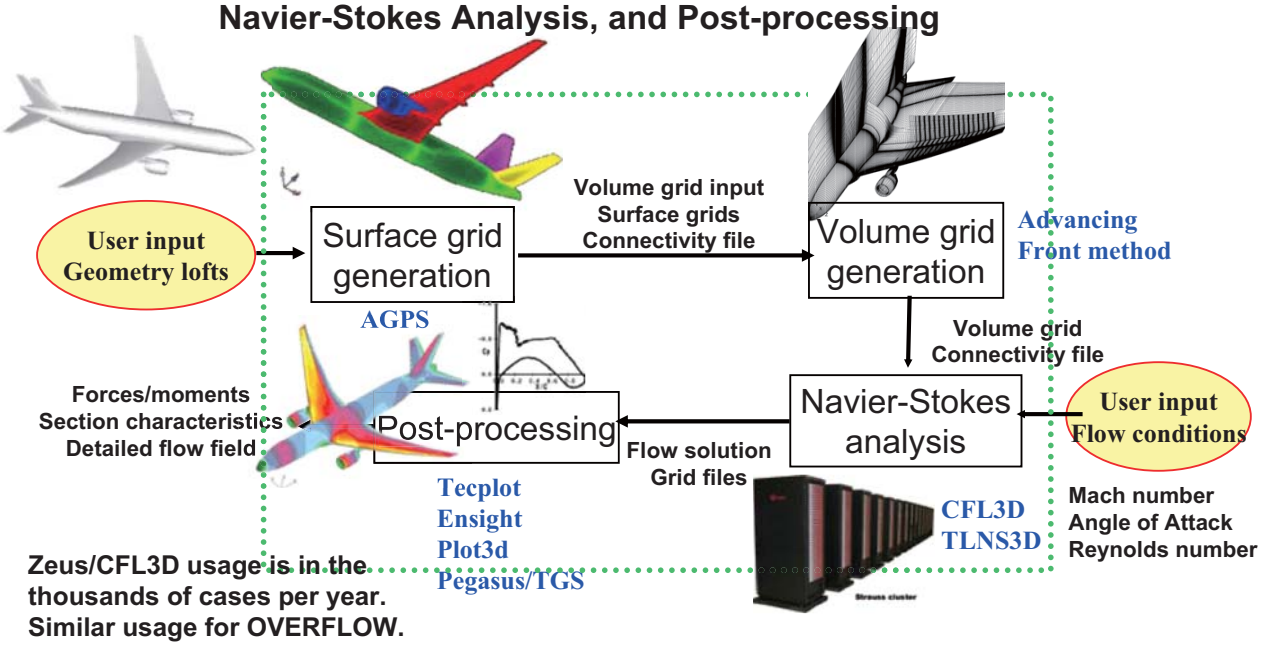
Stable, Packaged Software Solutions – Zeus/CFL3D

Driver for Surface Grid Generation, Volume Grid Generation, Navier-Stokes Analysis, and Post-processing



Zeus/CFL3D usage is in the thousands of cases per year. Similar usage for OVERFLOW.

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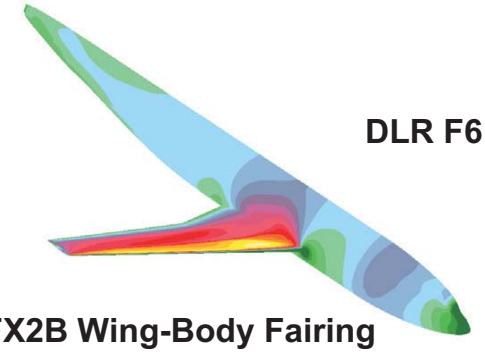
Case Study – 3rd AIAA Drag Prediction Workshop

An example of predictive CFD. All CFD solutions completed at least a year prior to wind tunnel test!

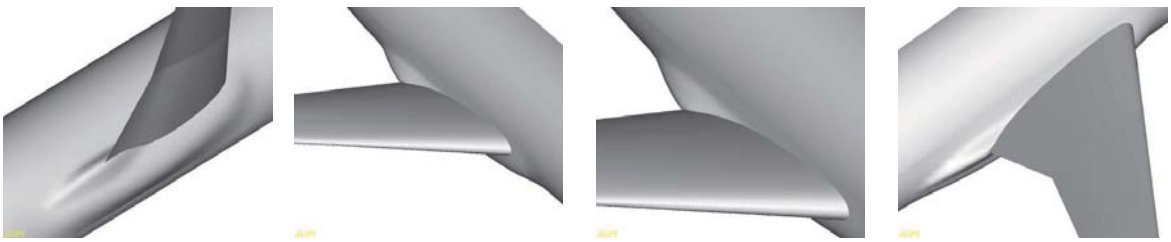


DLR F6 Wing-Body

Original Reference for base DLR-F6 geometry: AIAA 2001-2414.pdf

FX2B Reference: AIAA 2005-4730.pdf

FX2B Wing-Body Fairing



NASA completed a test of these configurations at the NTF in October 2007

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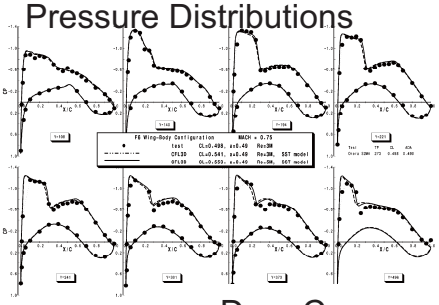
Zeus/CFL3D system – F6 with and without FX2B Fairing

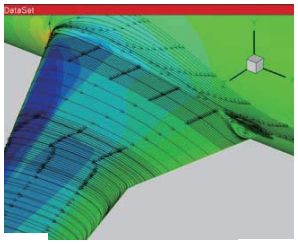
Four Grids - 2.6 to 31 Million Cells

Four combinations - SA or SST Turbulence Models

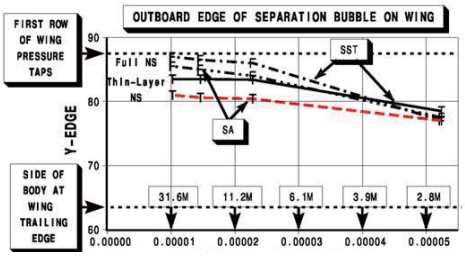
- Thin-Layer or Full Navier-Stokes Terms

Pressure Distributions

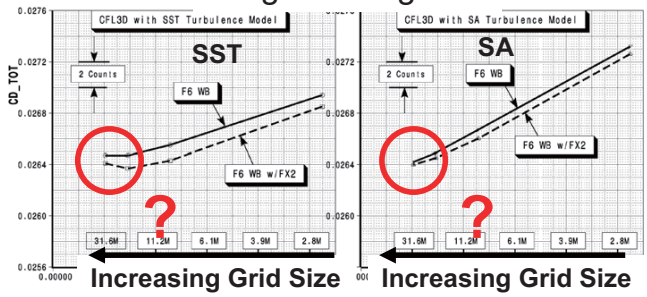




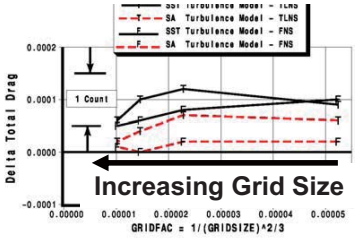
Separation Bubble Extent



Drag Convergence



Drag Increment Convergence



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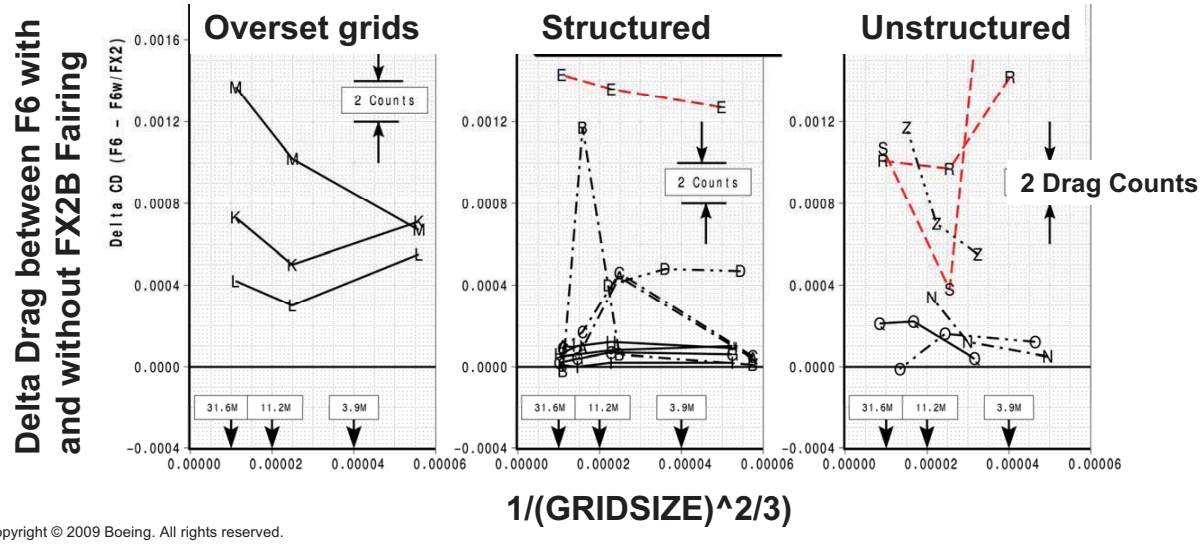
Drag Increment Predictions by DPW3 Participants

F6 Wing-Body w/wo FX2, MACH = 0.75
Re = 5 Million, Fixed CL=0.50

Delta CD (WB - WB w/FX2)

These are results from codes that are considered validated!



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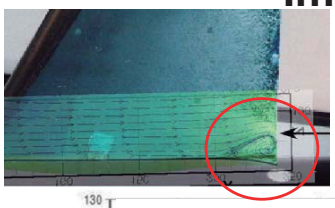
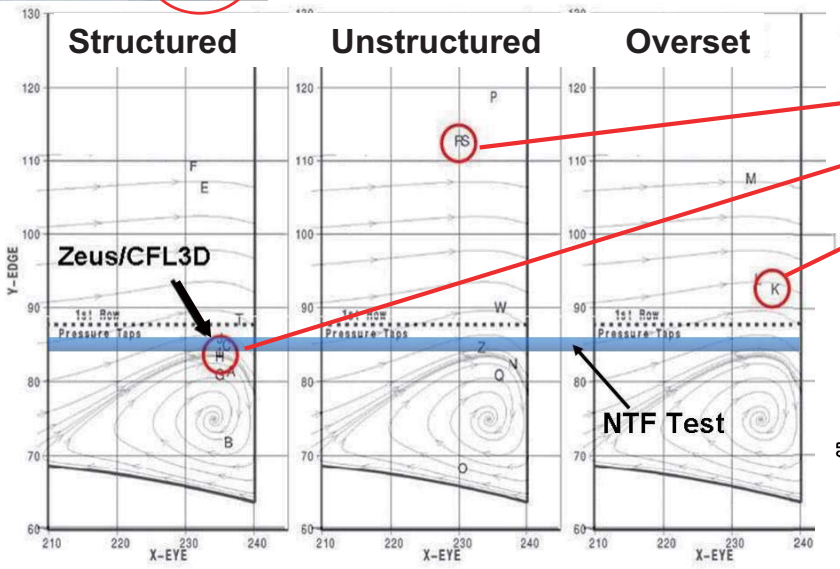
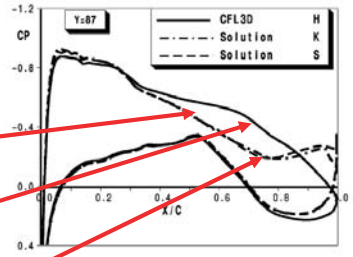
Impact of Separation Bubble Size on Wing Pressure Distribution



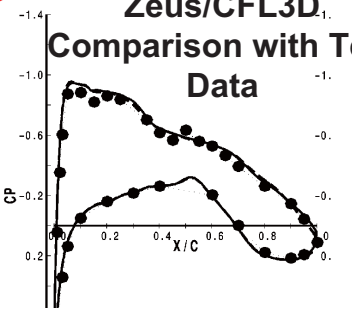
Extent of Separation Bubble from Various DPW3 Participants



Solutions at CL=0.50, Re=5M



Zeus/CFL3D Comparison with Test Data



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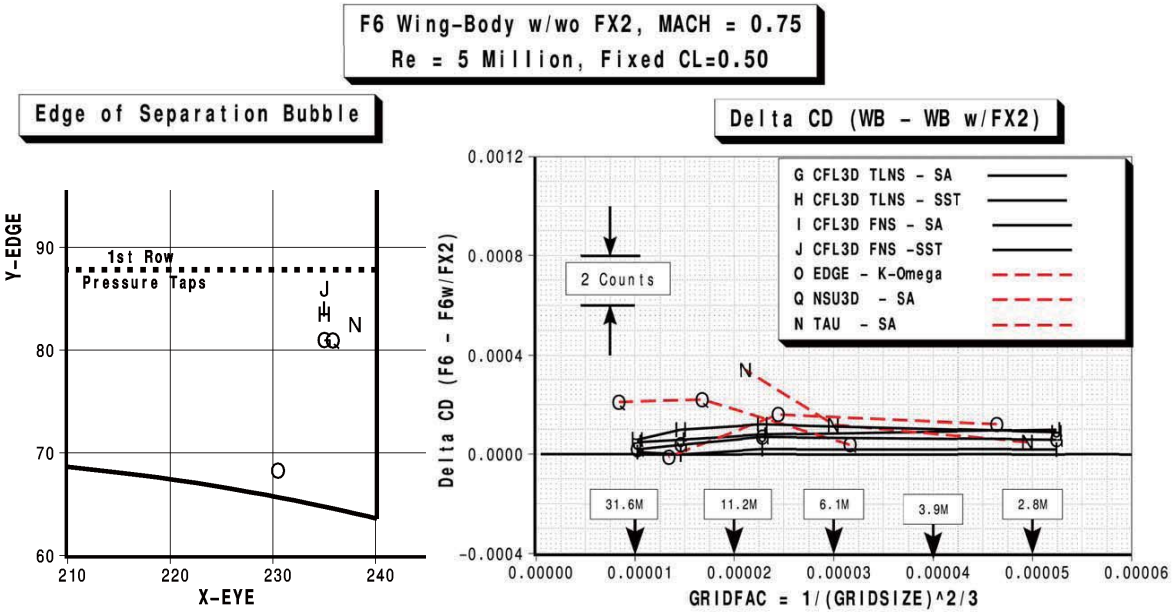
Drag Increment Predictions After Filtering Out

Predictions of Large Separation Bubble Pressure Distribution Anomalies



First presented in June 2006

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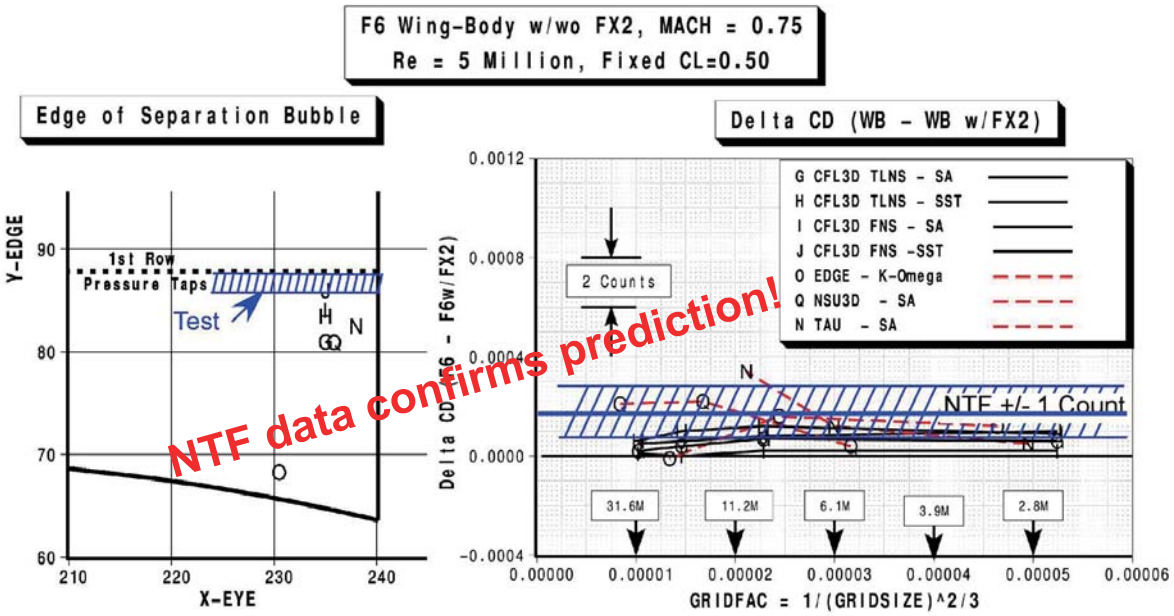
Pressure Distribution Anomalies



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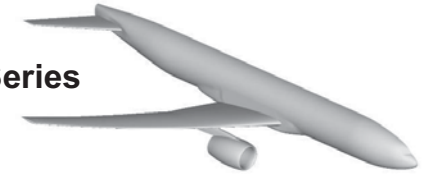
Stumbling Block to Building Confidence

Key to developing the confidence to use CFD in a predictive manner is the on-going, never-ending, validation process. Difficult to do in isolation and without access to a large experimental data base!

- Open workshops very valuable for information exchange
  - CAWAPI F-16XL project
  - AIAA Drag Prediction Workshop Series



- NASA Common Research Model
  - Public domain geometry and test data
  - Testing planned to start in 2009

- 4th AIAA Drag Prediction Workshop
  - June 20-21, 2009 – San Antonio, Tx

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Concluding Remarks

- Validation for an intended purpose is absolutely necessary for confident "predictive" use
  - Requires intimate knowledge of both CFD and experimental data
  - Agglomeration of comparisons at multiple conditions, configurations, code-to-code, code-to-test
- Not just a code but the entire CFD process
  - Geometry, grid generation, solver, post-processing
  - Users
- Need consistent, repeatable CFD processes
  - Packaged processes for "standard" configurations
  - Minimize user "knobs"
  - Standardized grid generation

It is difficult if not impossible to put a precise numerical definition on what is CFD validation and when CFD is "good enough" but I know it when I see it. And to know it requires seeing a lot of it to develop that confidence that it is "good enough."

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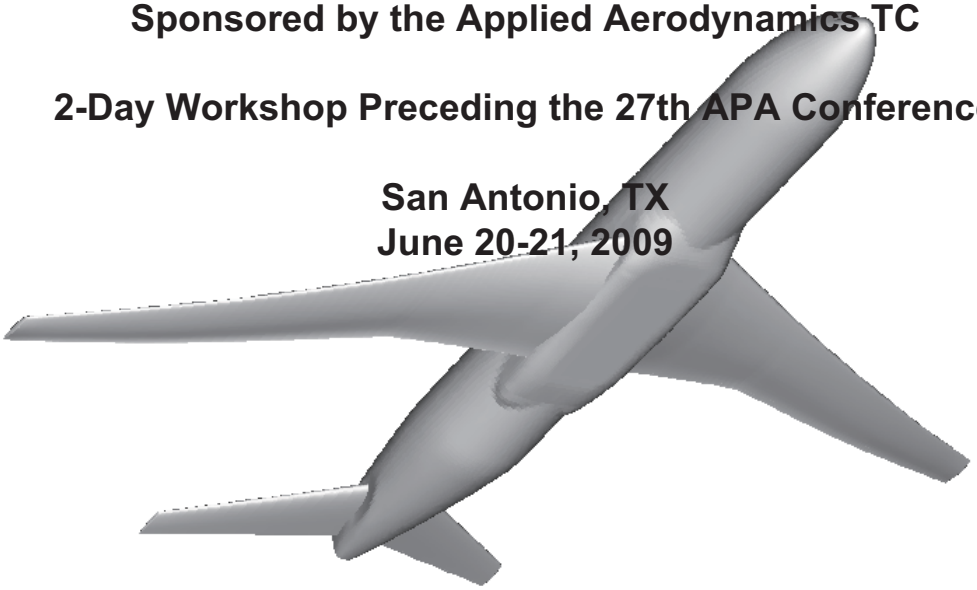
4th AIAA CFD Drag Prediction Workshop

Sponsored by the Applied Aerodynamics TC

2-Day Workshop Preceding the 27th APA Conference

San Antonio, TX
June 20-21, 2009



http://aaac.larc.nasa.gov/tsab/cfdlarc/aiaa-dpw/

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Case 1 – Grid Convergence and Downwash Studies:

1. **Grid Convergence study**
   at Mach=0.85, C_L=0.500 (±0.001)
   - Tail Incidence angle, i_H = 0°
   - Coarse, Medium, Fine, Extra-Fine Grids
   - Chord Reynolds Number 5x10^6 based on c 275.80 in
2. **Downwash Study** at M=.85
   - Drag Polars for alpha= 0.0°, 1.0°, 1.5°, 2.0°, 2.5°, 3.0°, 4.0° (?)
   - Tail Incidence angles i_H = -2°, 0°, +2°, and Tail off
   - Medium grid
   - Chord Reynolds Number 5x10^6 based on c_{REF}= 275.80 in
   - Drag delta tail off vs. on (trimmed, derived from the three polars at i_H = -2°, 0°, +2°)

Case 2 (Optional) – Mach Sweep:

1. **Drag Polars** at:
   - Mach=0.70, 0.75, 0.80, 0.83, 0.85, 0.86, 0.8
   - C_L=.400, .450, .500 (±0.001)
   - Untrimmed, Tail Incidence angle, i_H = 0°
   - Medium grid
   - Chord Reynolds Number 5x10^6 based on c 275.80 in

Case 3 (Optional) – Reynolds Number Study:

Reynolds Number study at Mach=0.85, C_L=0.500 (±0.001)
- Tail Incidence angle i_H = 0°
- Medium grid
- Rn=5x10^6, 20x10^6 based on c_{REF}= 275.80 in

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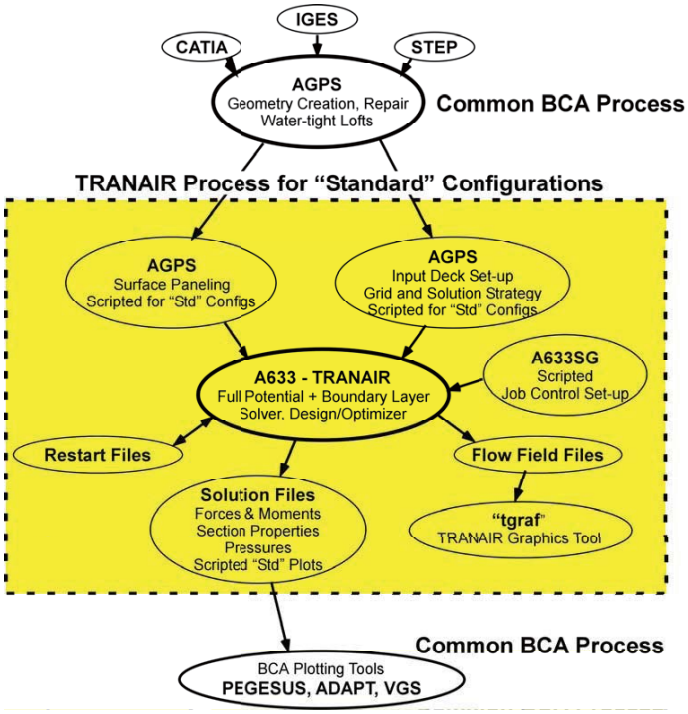
Stable, Packaged Software Solutions – TRANAIR

Scripted and Packaged for a "Standard" Class of Configurations

- Integral part of the engineering process
- Reduces solution flowtime
- Improves consistency and repeatability of results
- Uses common BCA processes
- Improves productivity

TRANAIR usage is in the 10's of thousands of cases per year



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Wind Tunnel Data Corrections

Clear tunnel flow conditions are subject to small variations in pressure and flow direction. The introduction of the wind tunnel model further disturbs these quantities away from "free-air".

- Mach Number – Function of total and static pressure
  - Centerline pressure vs. static measurement
  - Static pressure change due to model presence – "Mach Blockage"
- Angle-of-Attack – A derived quantity – physical angle + corrections for:
  - Flow angularity – "Up-flow"
  - Lift interference – "δ_o" – Model to tunnel size, tunnel wall ventilation, Mach
- Drag – Measured force corrected for angle-of-attack, + corrections for:
  - Clear tunnel buoyancy
  - Solid blockage buoyancy
  - Internal cavity pressures
  - Normalized skin friction
- Tare and Interference – can effect all quantities, specific to model, tunnel, Mach number

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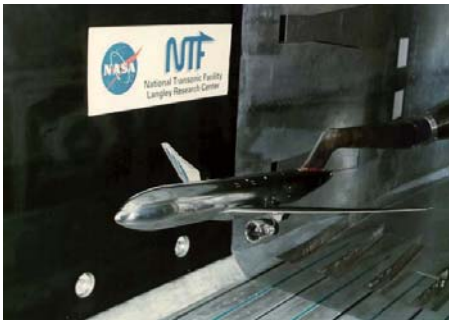
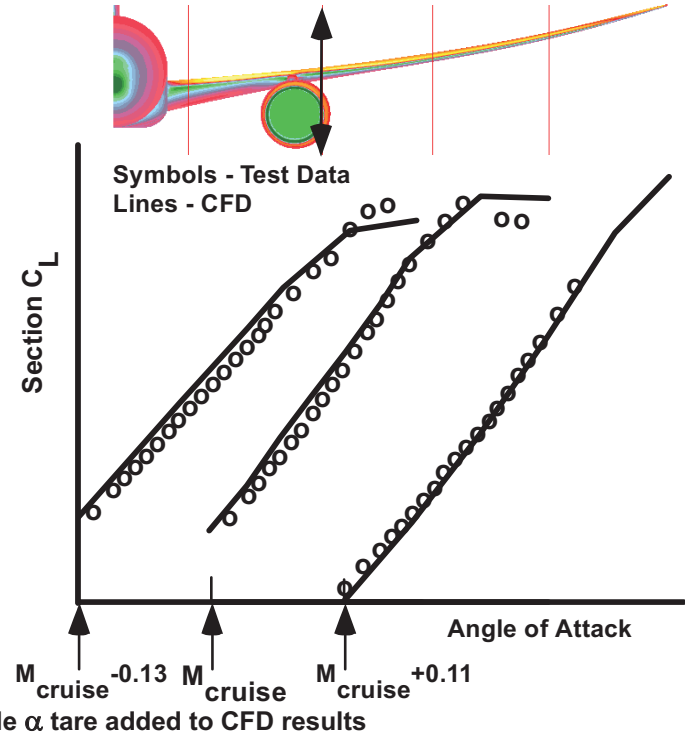
Mach Number Effects on Section Lift

- Use CFD to determine initial loads prior to a wind tunnel entry
- Consistent process yield consistent solutions
- Consistency yields confidence





Single α tare added to CFD results

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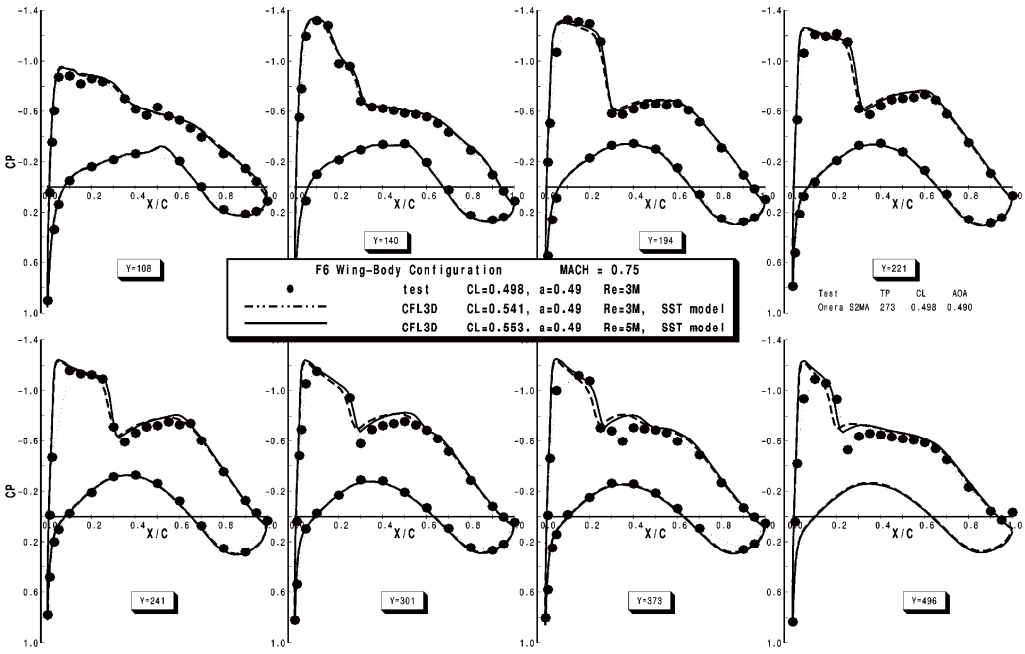
F6 Wing-Body - Wing Cp's – Comparison with Original ONERA test at Re=3M – Solution at Re=5M also shown



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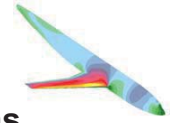
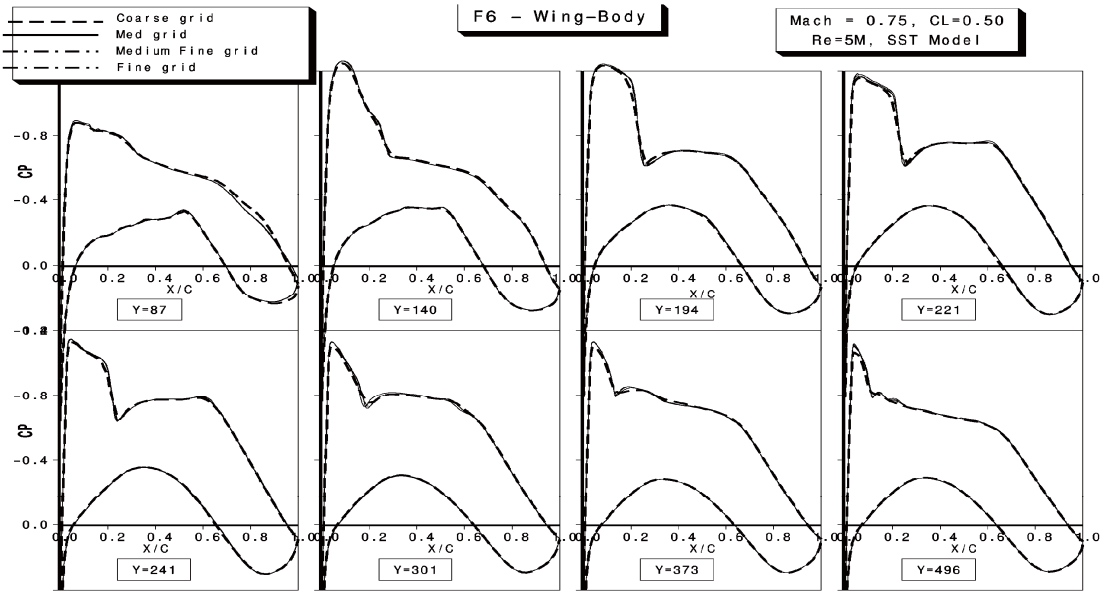
F6 Wing-Body - Wing Cp's – Grid Convergence

Four Grids - 2.6 to 31 Million Cells for each configuration
Four combinations - SA or SST Turbulence Models
- Thin-Layer or Full Navier-Stokes Terms





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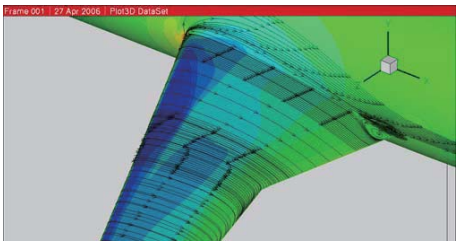
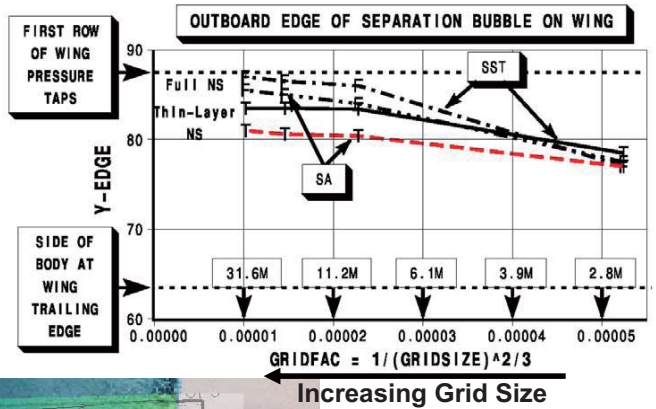
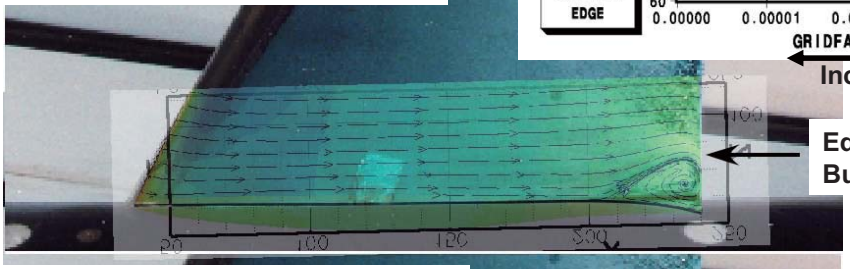
F6 WB Separation Bubble on Wing – Turbulence Modeling



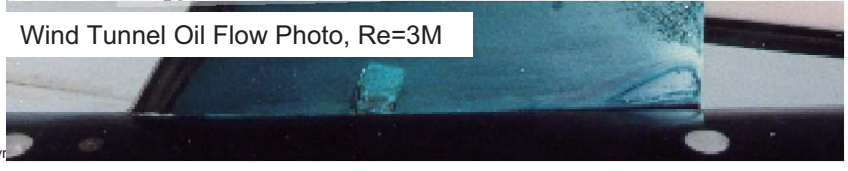
Overlay of Computed Streamlines, SST Turbulence Model, Re=5M





Edge of Separation Bubble on Wing

Wind Tunnel Oil Flow Photo, Re=3M



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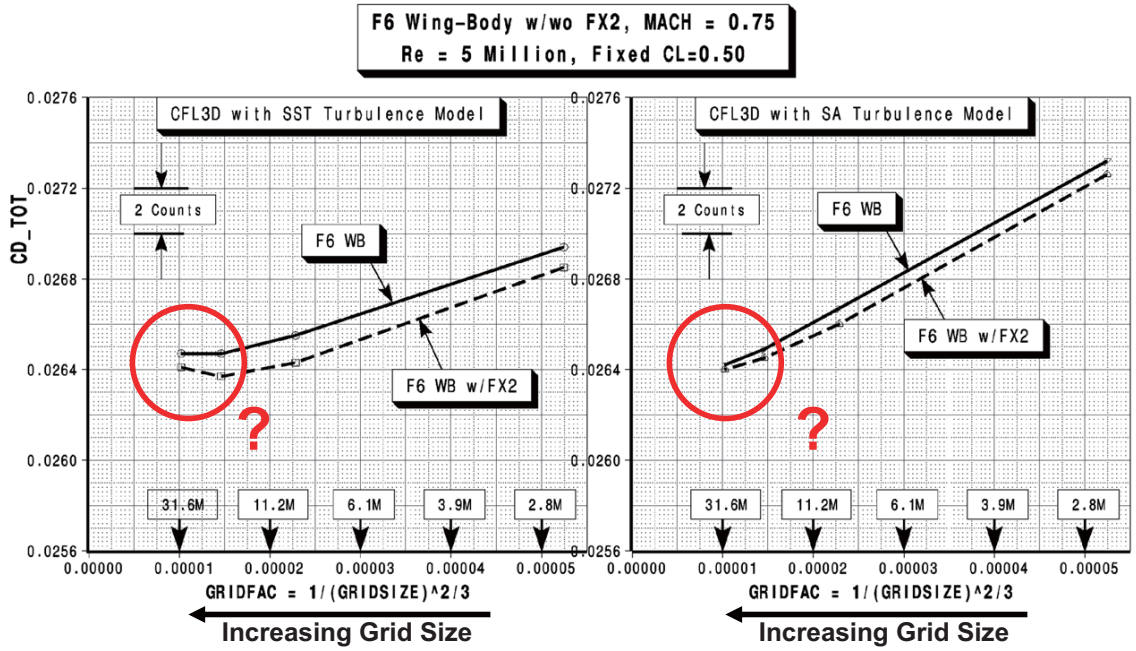
Second Workshop on Integration of EFD and CFD

Drag Convergence with Thin-Layer CFL3D, M=0.75, CL=0.50



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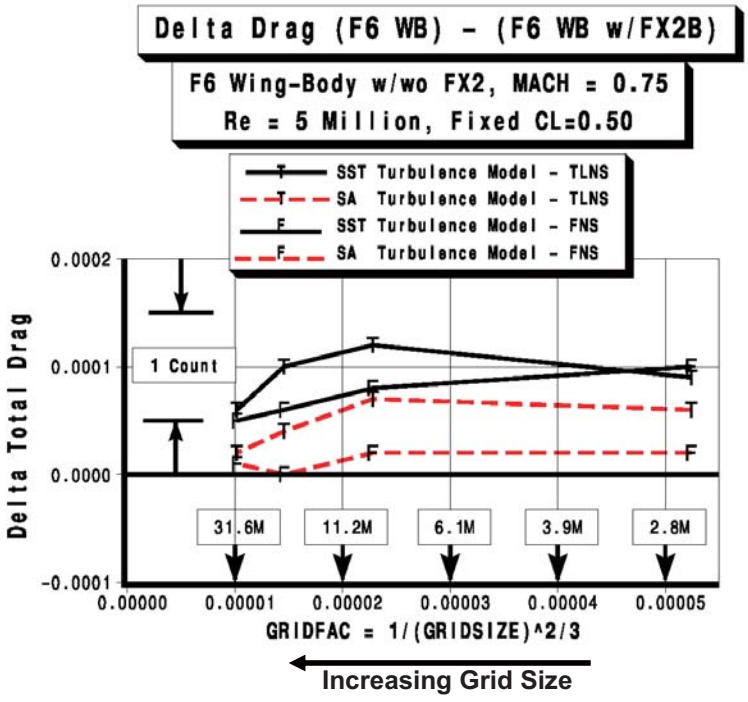
Second Workshop on Integration of EFD and CFD

Drag Increments between Configurations



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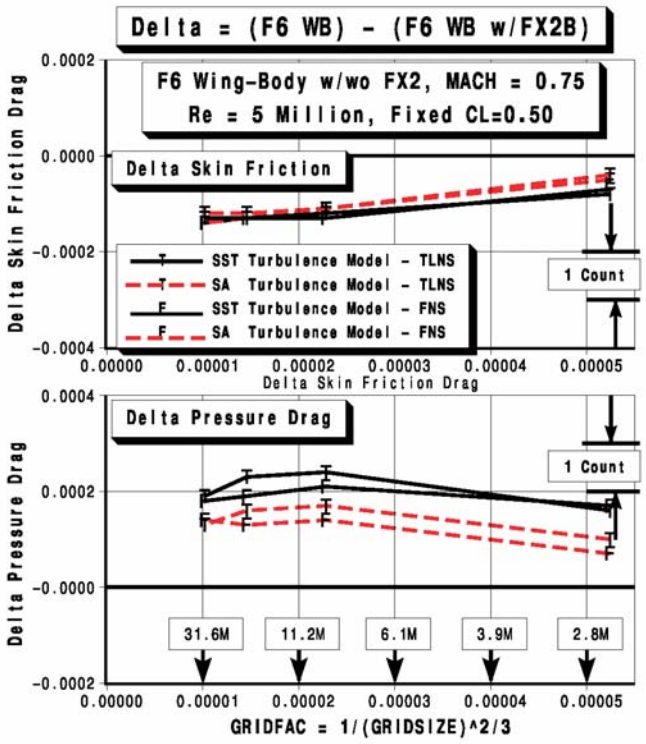
Second Workshop on Integration of EFD and CFD

Component Drag Increments



Drag increment variation is due to pressure drag changes we believe are related to the separation bubble prediction

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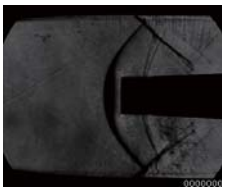


第2回EFD/CFD融合ワークショップ
宇宙航空研究開発機構　調布航空宇宙センター
2009年2月24日（火）

普段着のEFD/CFD連携
～超音速抗力低減を題材として～

This is Our Usual EFD/CFD Collaboration
- An Example in Supersonic Drag Reduction Study -

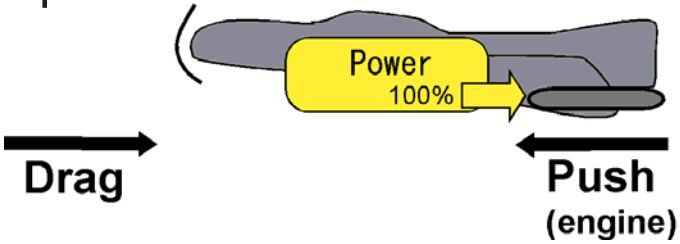
名古屋大学大学院工学研究科航空宇宙工学専攻
佐宗 章弘，酒井武治，松田淳，関谷洋平，Jae Hyung Kim
SASOH,　SAKAI,　MATSUDA, SEKIYA,　KIM
（EFD）（CFD/EFD）　（EFD）　（EFD）　（EFD/CFD）

Definition of Problem

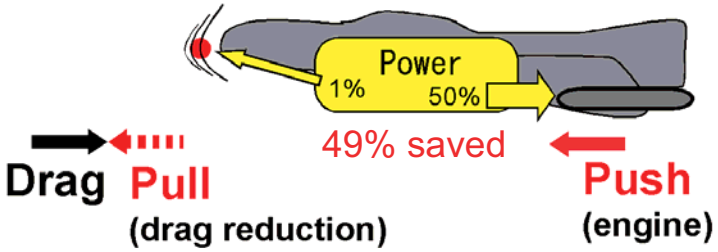
Push-Pull hybrid propulsion: A wave drag can be efficiently decreased with energy depositions ahead of a body.

(Power for propulsion) = (Drag) × (Speed)

-w/o energy deposition



-w/ energy depositions



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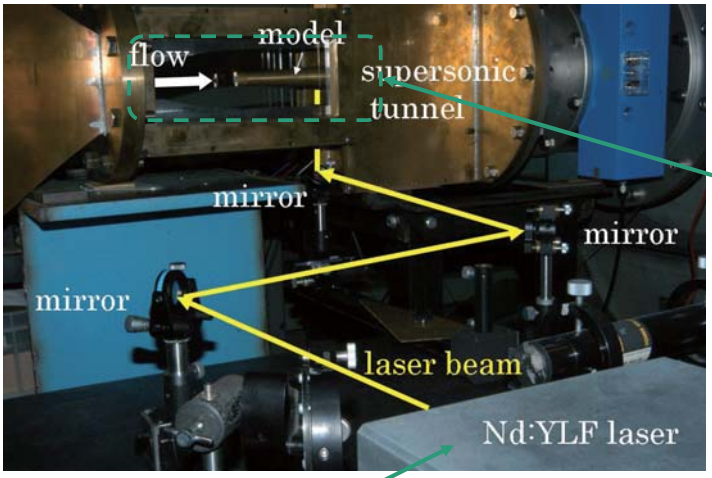
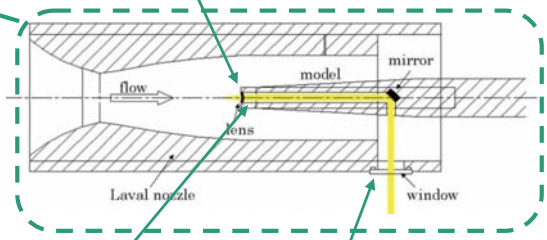
Configuration

Control parameters: Flow Mach number/Laser energy/ Laser pulse repetition frequency/Location of energy deposition

Results: Decrement in drag/efficiency of energy deposition





Plane-convex lens
(f=10-30mm)

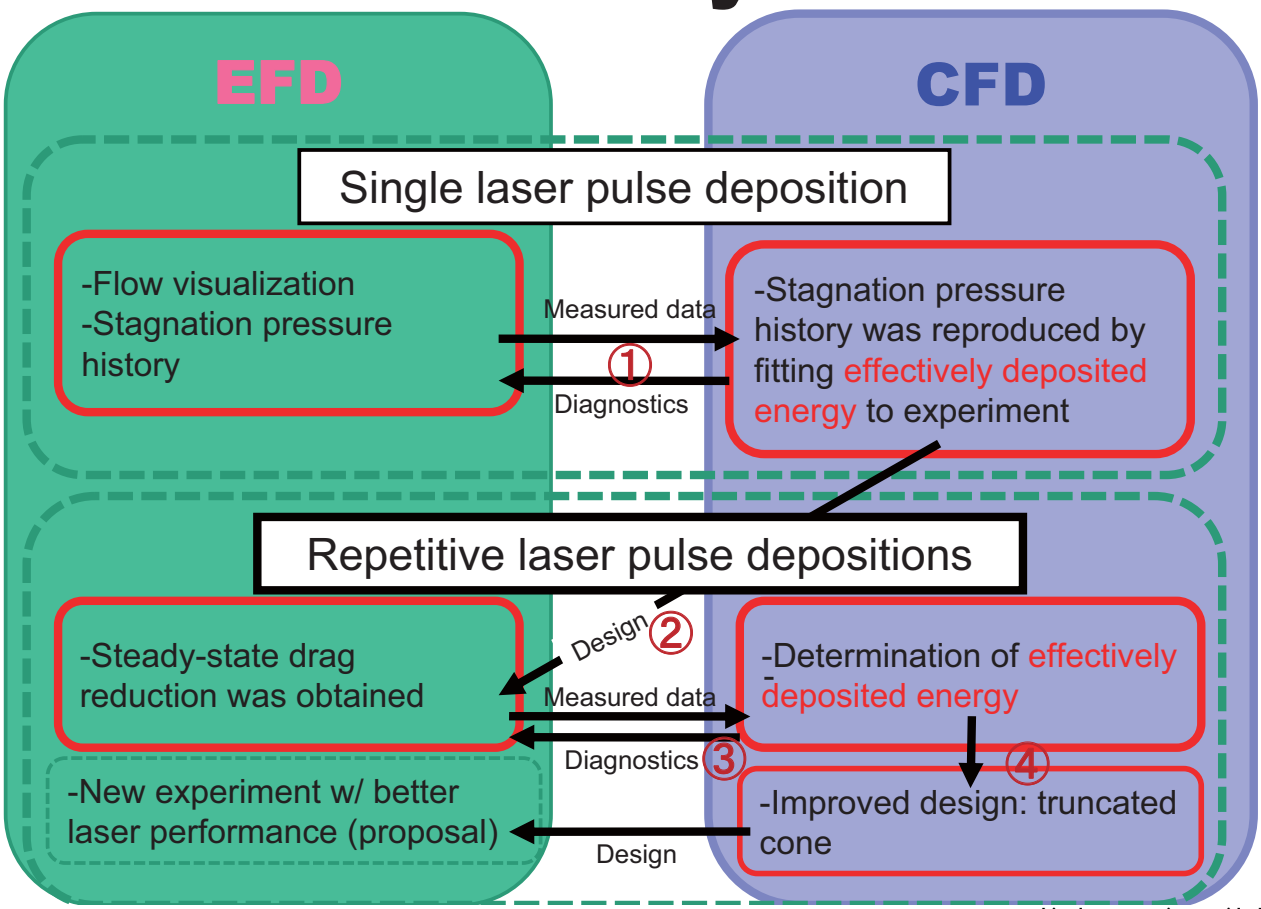
BK7 window

20mm-dia. cylinder

Nd:YLF laser (PowerEdge co., wavelength; 1047nm, repetition frequency; 10 kHz max., average power; 80 W max., 5mm × 5mm square beam)

3

History



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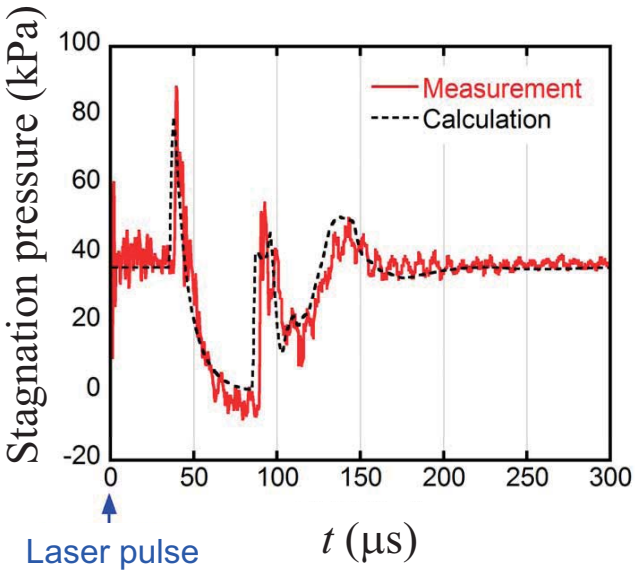
1st Step:
Single pulse operation
(presented @ last workshop)

Data Fitting in Stagnation Pressure History



EFD: @operation temperature out of guarantee (yet temporally accurate)

CFD: Effectively input energy should be given

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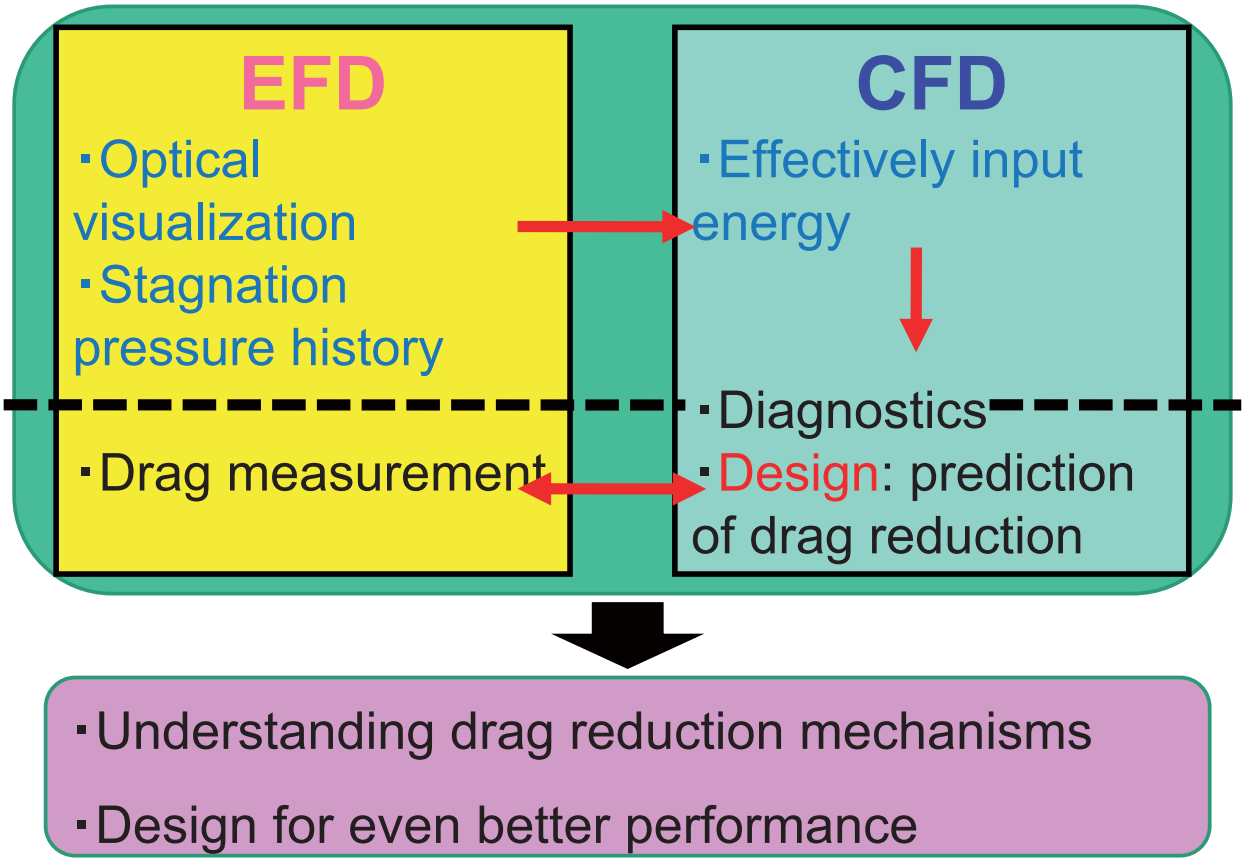
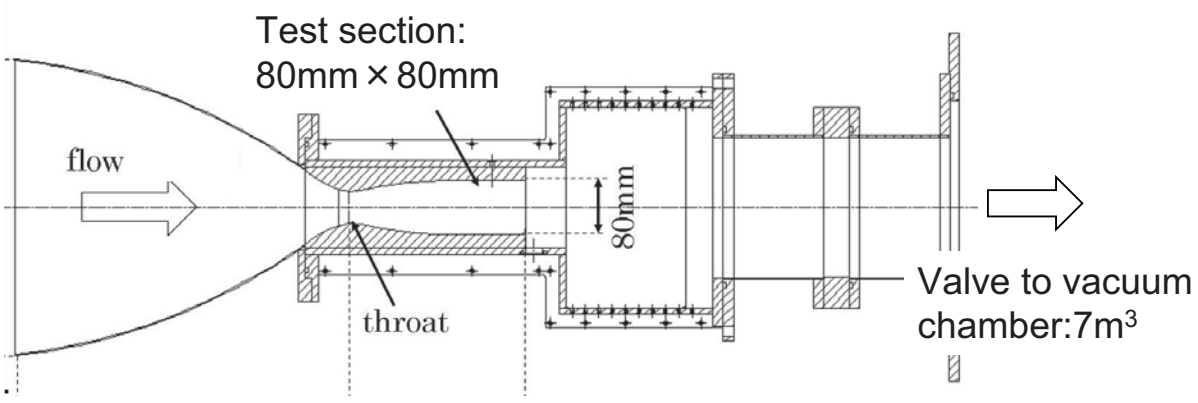
EFD/CFD Integration Gets More



2nd Step: In-Draft Wind Tunnel

Designed w/ method of characteristics
→ Boundary layer correction using CFD
→ Experimental performance examination



-Flow Mach number =2.0
-Run time = 5s
-Total pressure =101kPa
-Static pressure = 14.7kPa
(-Static temperature= 167K)

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3d Step: Steady-State Drag Measurement

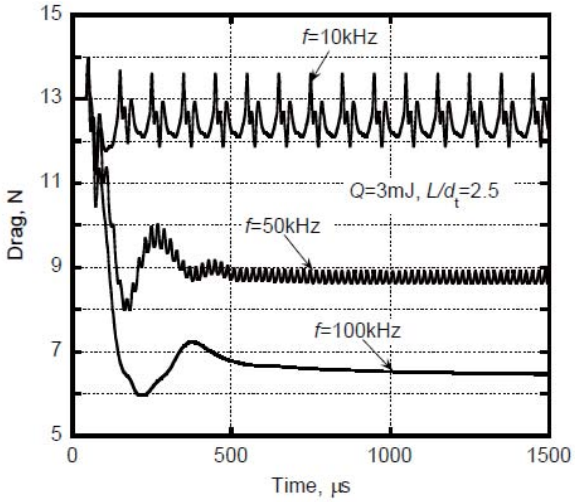
- Experimental evaluation of steady-state (time-averaged) drag reduction using up-to-10-kHz repetitive laser pulses.
  - **More accurate** than spatiotemporally integrating pressure field.
  - Real performance with **interactions among pulses**

- Understanding related flow mechanics through numerical & experimental **diagnostics**.

9

4th Steps: New Insight from CFD (Repetitive-Pulse Effect)

Single-pulse performance cannot be applied if the repetition frequency is high enough for interactions to be significant.



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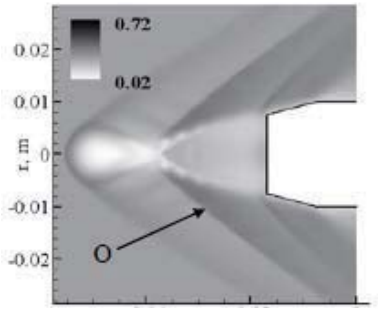
New Design by CFD: Truncated Cone (Sakai 2009):

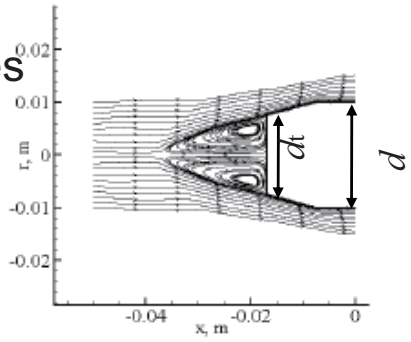
~Small drag & high efficiency~

Quasi-steady flowfield
(Q=3mJ, f=100kHz)

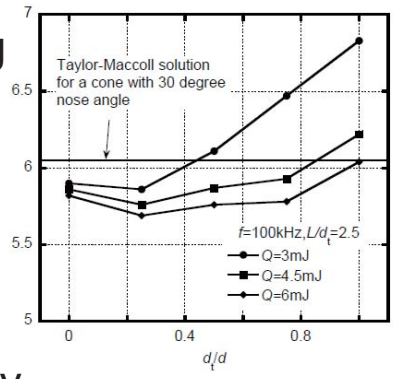
Isopycnics



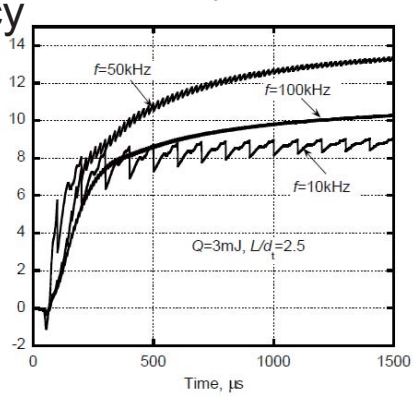
Streamlines



Drag



Efficiency



Summary: Do not forget/Let's start basic EFD/CFD interactions

Brief History truncated cone in four months:

- **Sakai** & **Sasoh** discussed **truncated cone** idea.
- **Sakai** ran a computer for truncated cone operation.
- **Sakai** numerically obtained the truncated cone performances, which were pretty good!
- **Sekiya** designed a truncated cone for experiment.
- **Sakai** already started writing a paper.
- **Sakai** predicted drag reduction available with existing facility (10 kHz was not high enough, 50 kHz would yield best efficiency)
- **Sekiya** conducted experiments (Large drag reduction w/ flat nose; drag reduction was too small w/ truncated cone – consistent to the prediction)
- **Sekiya** collected drag reduction data only with the flat nose, **Sakai** did numerical diagnostics, **Sasoh** started writing a proposal for a better performance laser, **Kim** proposed another idea for experiment, **Matsuda** supported arrangements for Kim's experiment

A Dairy on a day w/o any disturbance:

-Morning: Coming to the lab. w/ casual dresses (no ties), discussions in office, preparing for experiment in lab.

-Lunch: Together (students do not want to talk on research even in lunch time every day like Sakai & Sasoh do. Matsuda & Kim have their own lunch box which their wives cook)

-Afternoon: Experiment and discussions in lab.

-Evening: Staff go home (Sakai comes back), students stays longer if necessary.

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Numerical Computation and Experimental Measurement of Aerodynamic Noise

Present and Future

Chisachi Kato,
University of
Tokyo

Outline

- Background
- Numerical Prediction of Aerodynamic Noise
- Applications at Present
- Perspectives and Future Roles of Measurements

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Background

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Prediction and Reduction of Aerodynamic Noise

- **Aerodynamic Noise**
  - Generated from deformation of vortices
  - Drastically increase with increasing flow speed
- **Reduction of Aerodynamic Noise**
  - Crucial in development of various fans, airplane, automobiles, etc.
- **Expectations for Numerical Predictions**
  - Cost and/or time reduction for prototyping
  - Reduction of noise by identifying essential mechanism for noise generation
  - Prediction of noise under installation conditions

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Numerical Prediction of Aerodynamic Noise

Direct .vs. Decoupled Methods

- **Direct Computation of Aerodynamic Noise**
  - Provide information regarding detailed mechanism of noise generation
  - Applicable to feedback noise
  - Limited to simple geometries, particularly for noise from low speed flows
- **Decoupled Methods**
  - Based on acoustic analogy
  - No feedback assumed
  - Applicable to relatively complex geometories
  - Various methods have been proposed

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Applications at Present

Noise Generated from an Axial-flow Fan Subjected to Inflow Turbulence

Collaborator: Siegen University in Germany

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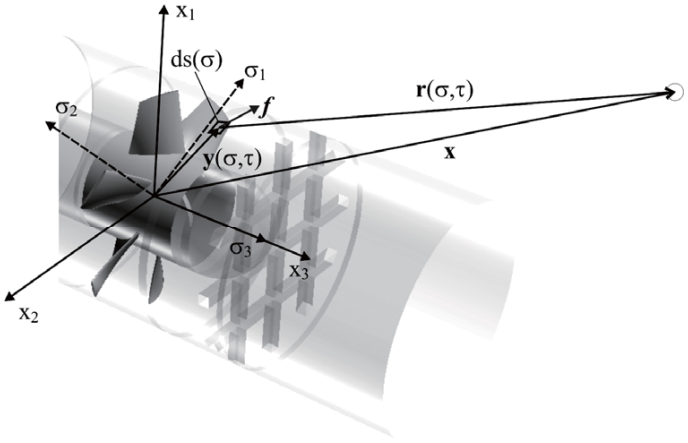
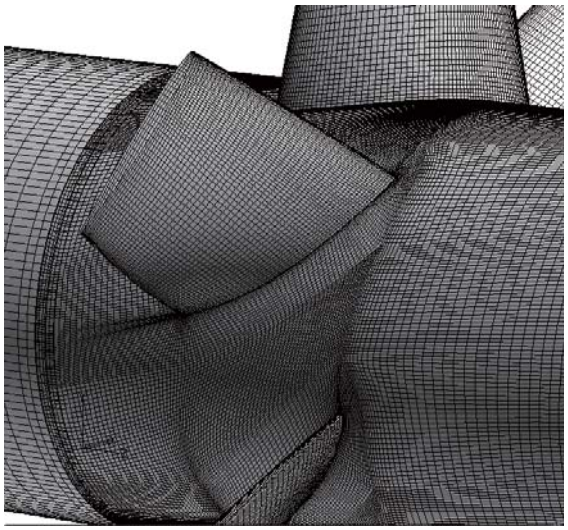
Computational Model

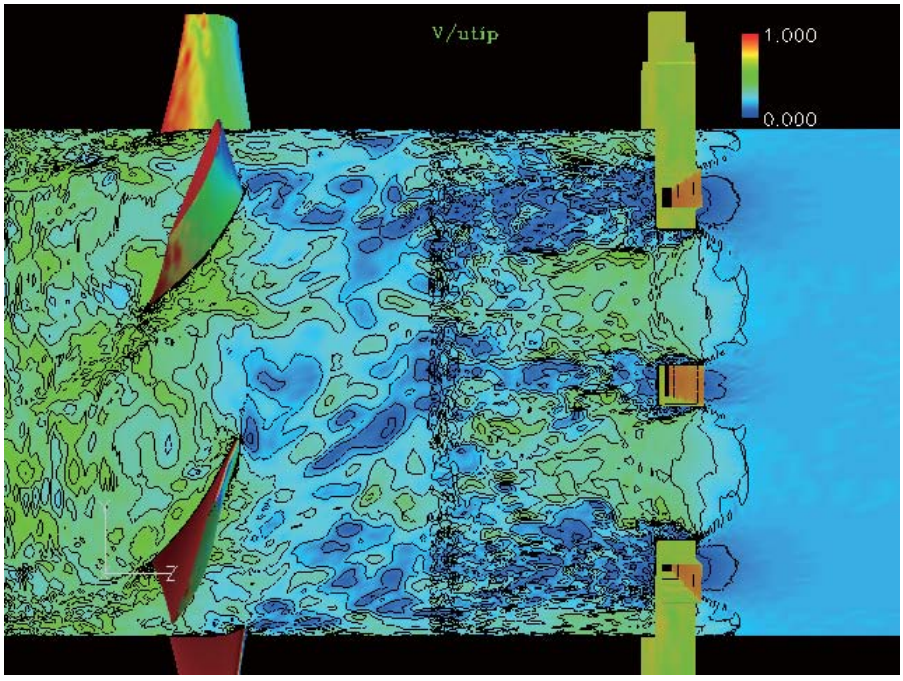




Ducted Fan Subjected to Turbulence Ingestion

Computational Grids on Blade Surface

Fluctuations of Instantaneous Streamwise Velocity



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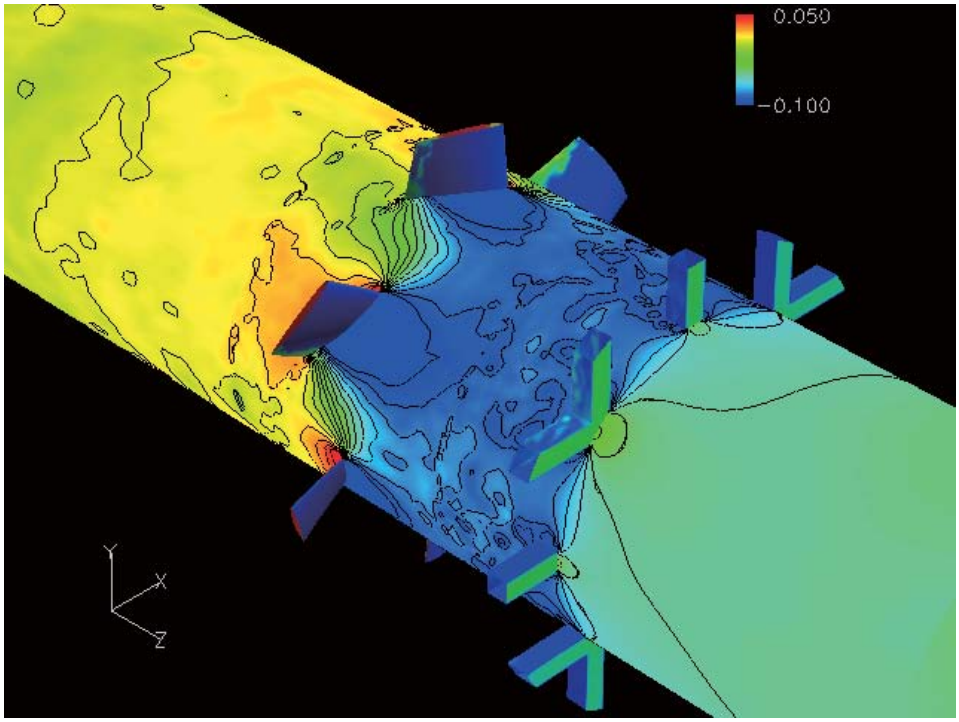
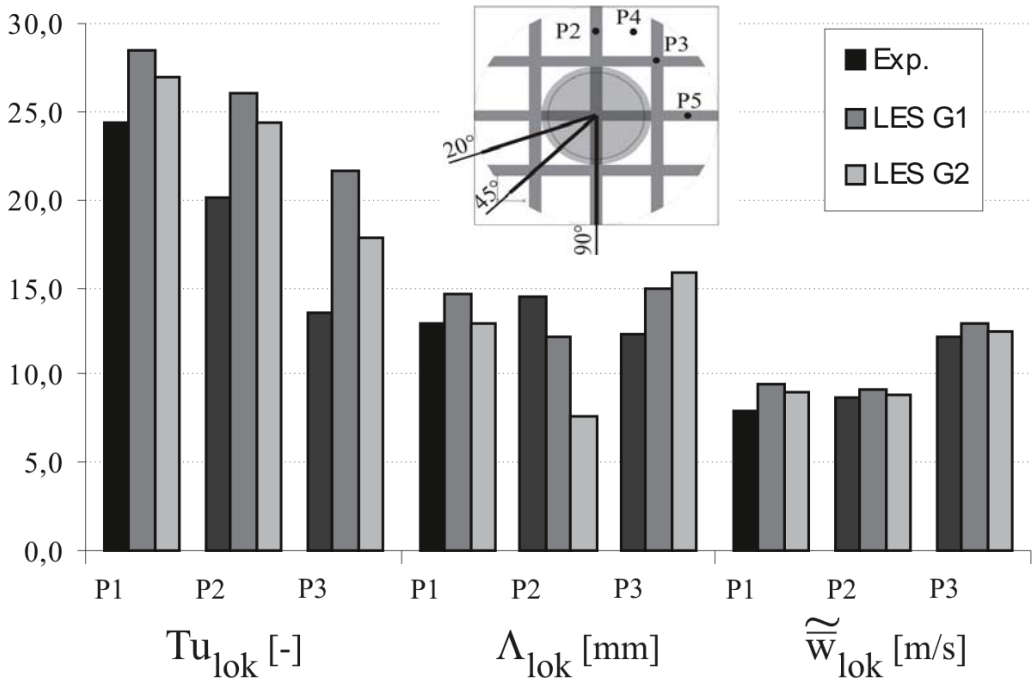
Fluctuations of Instantaneous Static Pressure



Comparisons of Turbulence Statistics behind Grid



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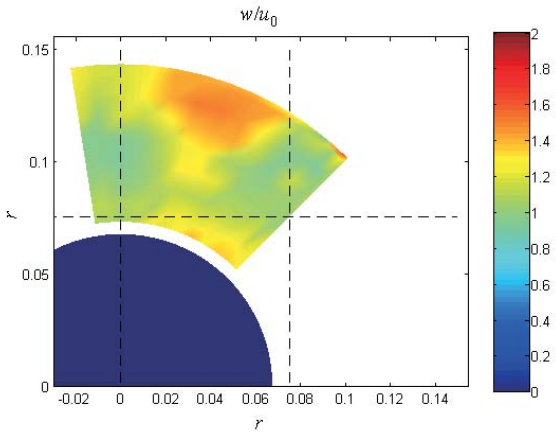
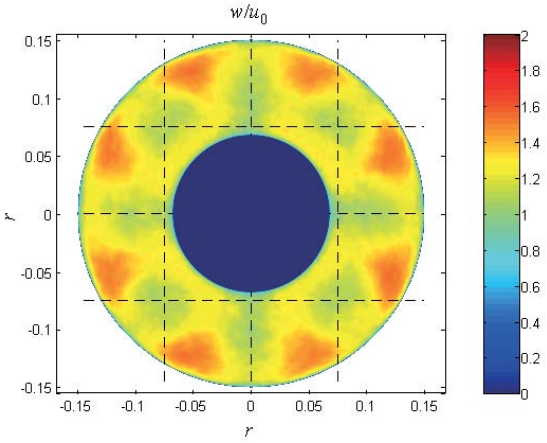
Comparison of Turbulence Intensity behind Grid

■ Incoming Turbulence Intensity



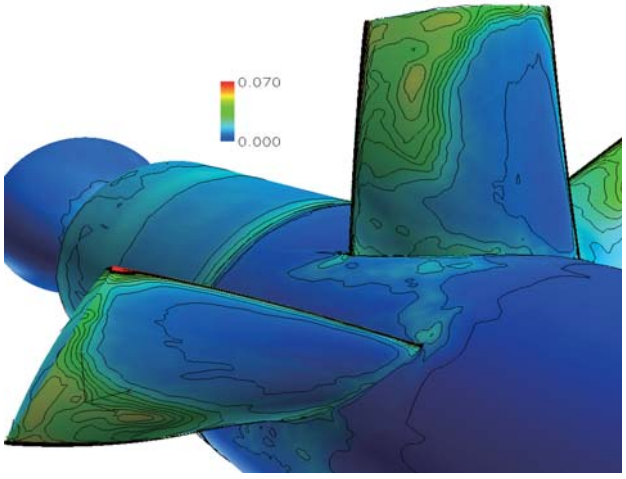
Measured by Hot Wire



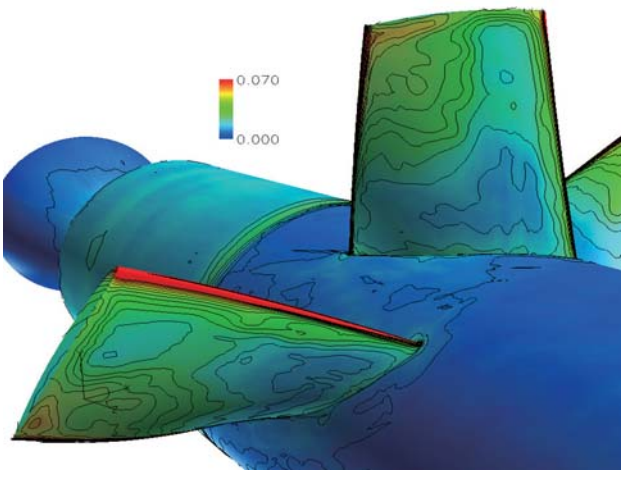
Computed by LES

Comparison of Surface Pressure Fluctuations

Root-mean-square Value of C_P



Clean Inflow Case



Turbulent Inflow Case

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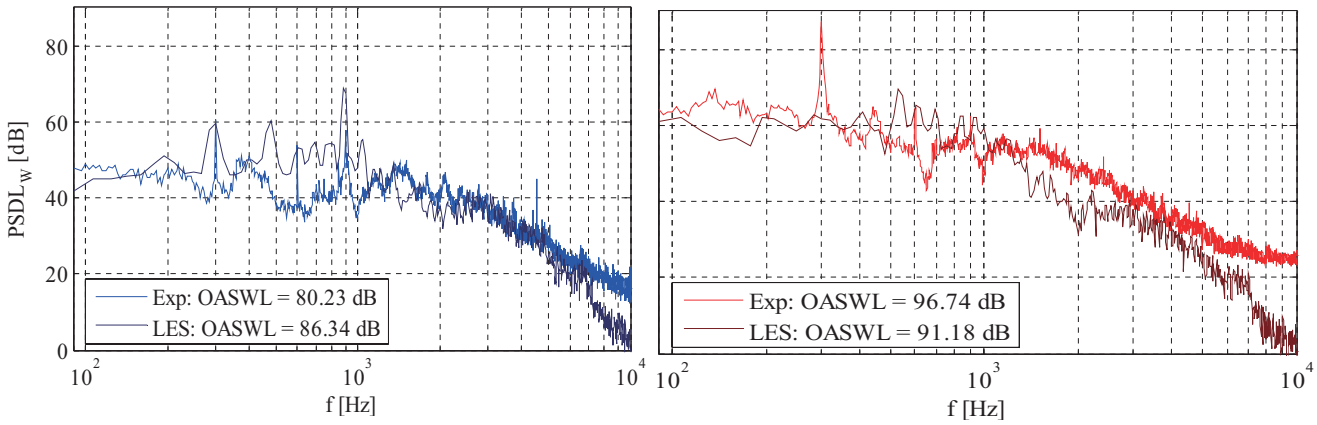
Comparison of Radiated Sound Pressure Levels

■ Far-field Sound Pressure Level



Clean Inflow **Turbulent Inflow**

Bypass Transition of Flat Boundary Layer and Resulting Sound

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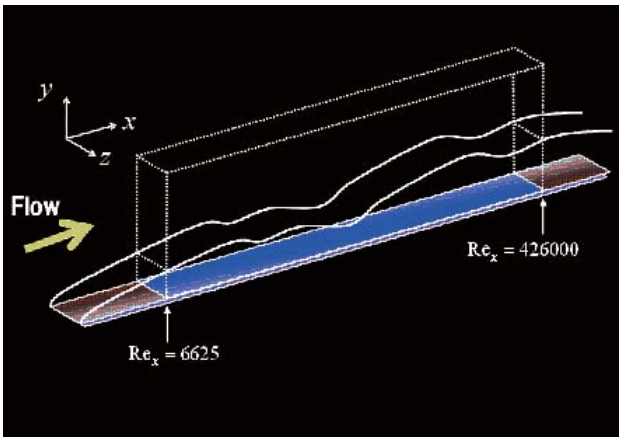
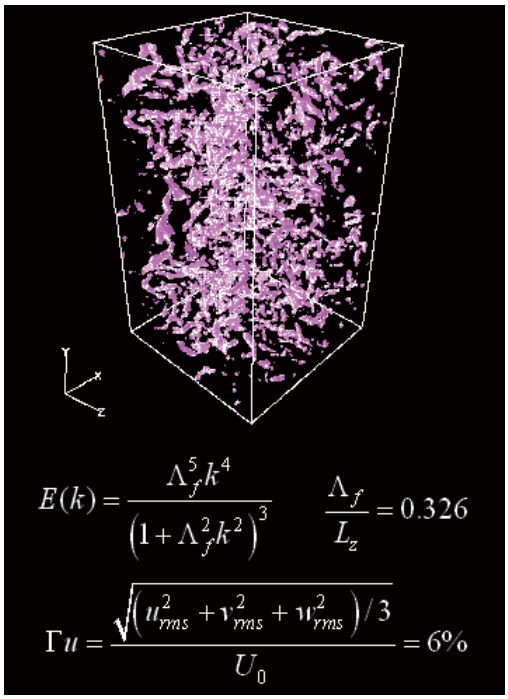
Computational Model



	# of nodes	Grid size
x	1134	Δ^+=14-38
y	70	Δ^+=1-76
z	76	Δ^+=15

Grid Resolution



Inflow Turbulence

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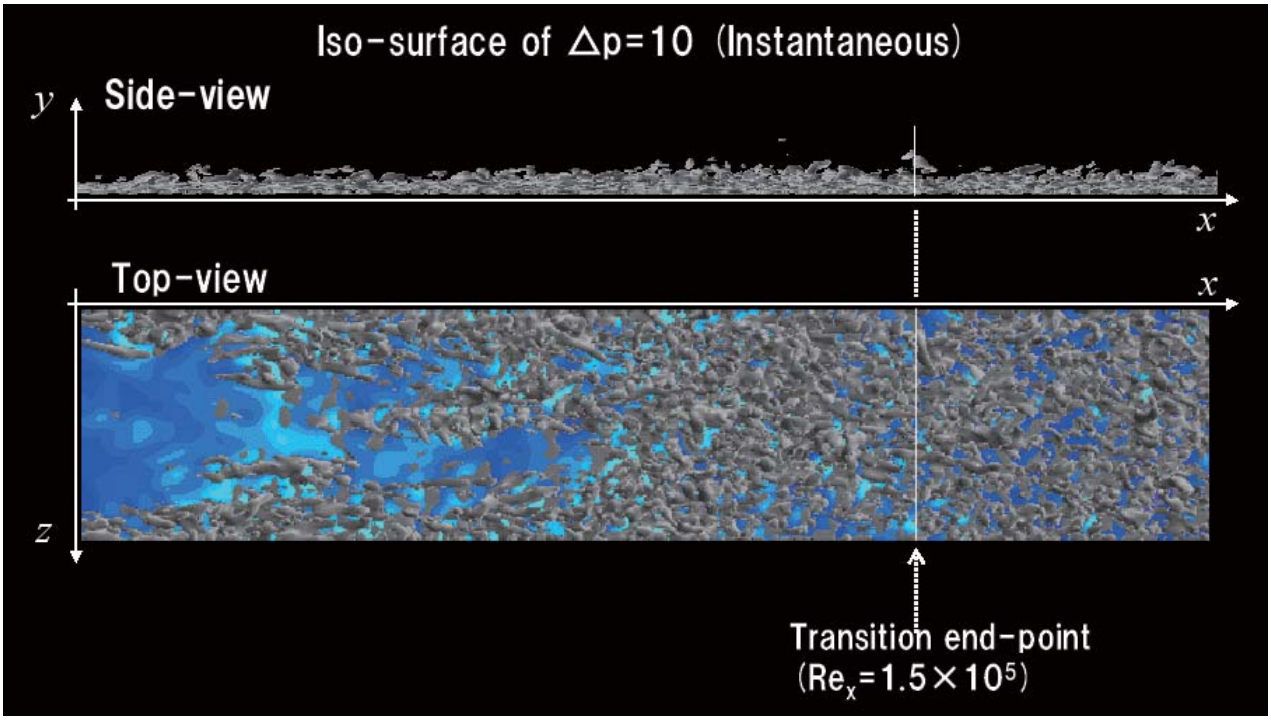
Instantaneous Vortical structure



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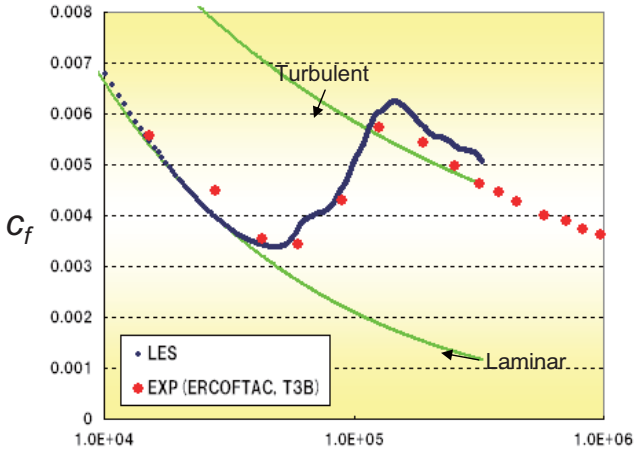
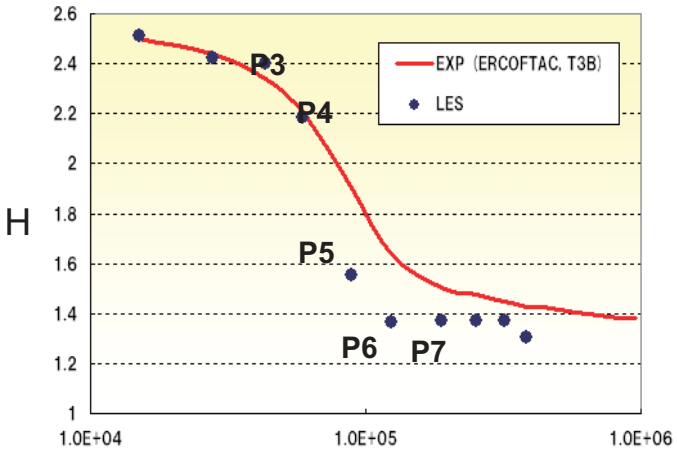
Comparison of Skin Friction and Shape Factor



Skin Friction Coefficient



Shape faction

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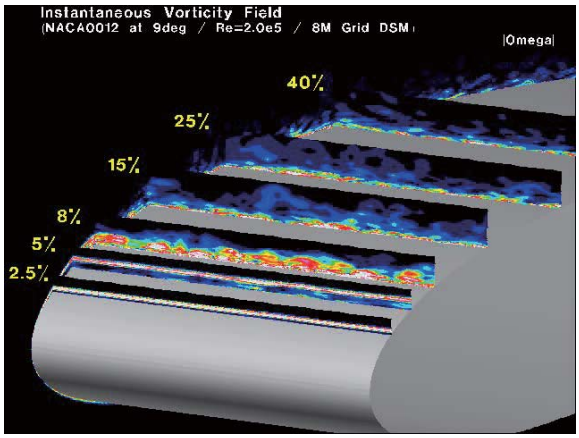
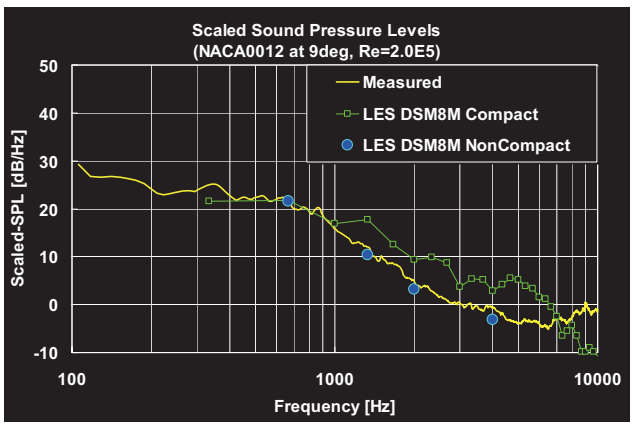
Prediction of Transitional Boundary Layer and Resulting Sound

NACA0012: Angle of attack=9 deg, Re=2.0x10^5



Vortical Structure near L. E.



Comparison of Far-field Sound Pressure Level

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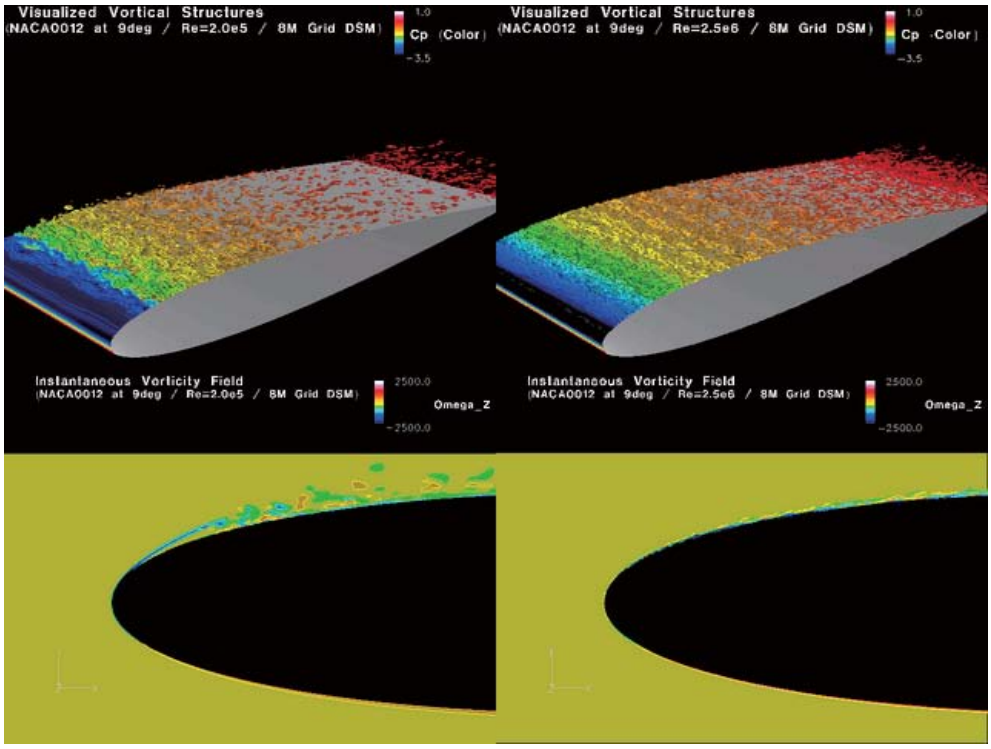
Effects of Reynolds Number on Transition Process (left: 2.0 x 10^5, right: 2.0 x 10^6)



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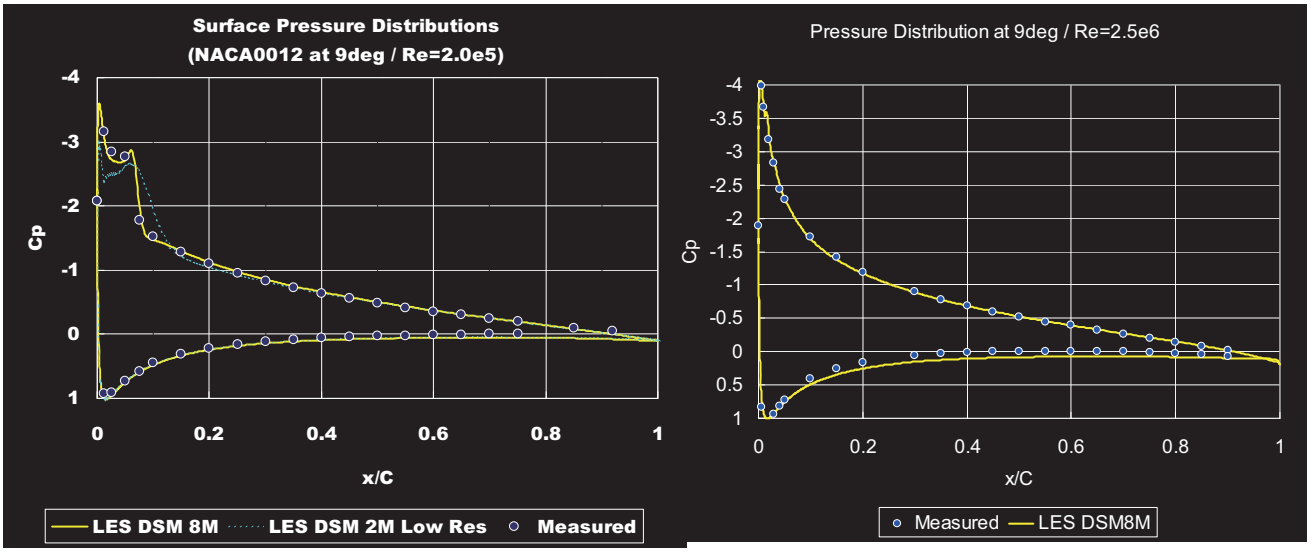
Effects of Reynolds Number on Surface Pressure Distributions

NACA0012: Angle of Attack = 9 deg.



■ Re = 2.0 x 10^5
(U_0=20m/s, C=0.15m)

■ Re = 2.5 x 10^6
(U_0=50m/s, C=0.75m)

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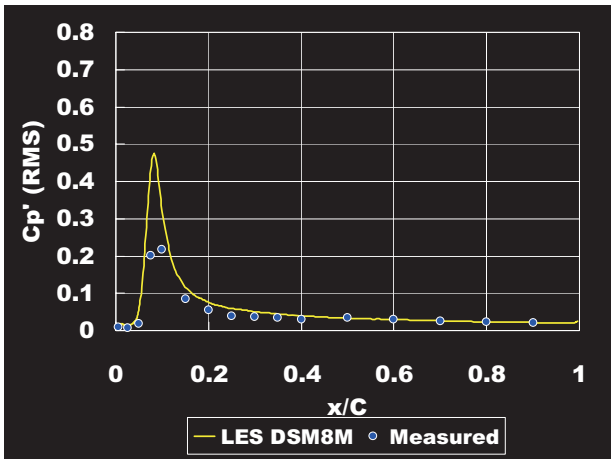
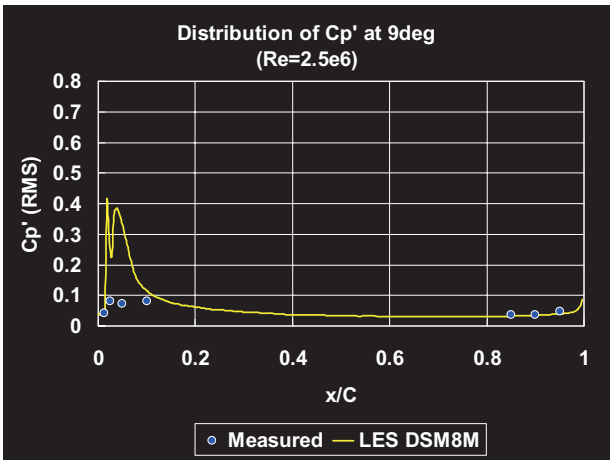
Comparison of Surface Pressure Fluctuations

Angle of Attack: 9 degrees



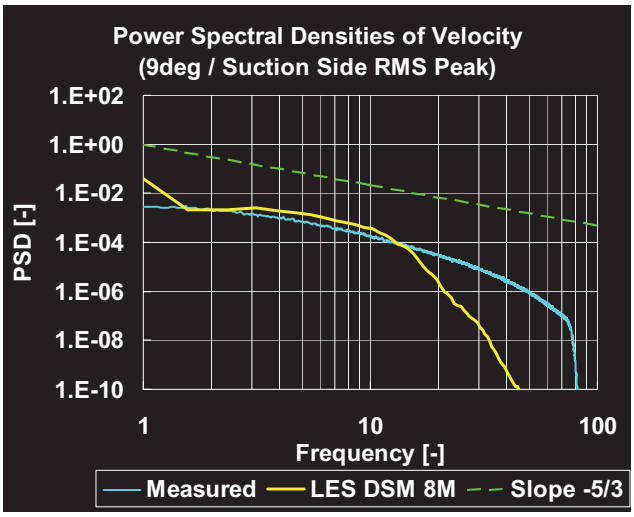
■ **Re = 2.0 x 10^5**
(U_0=20m/s, C=0.15m)



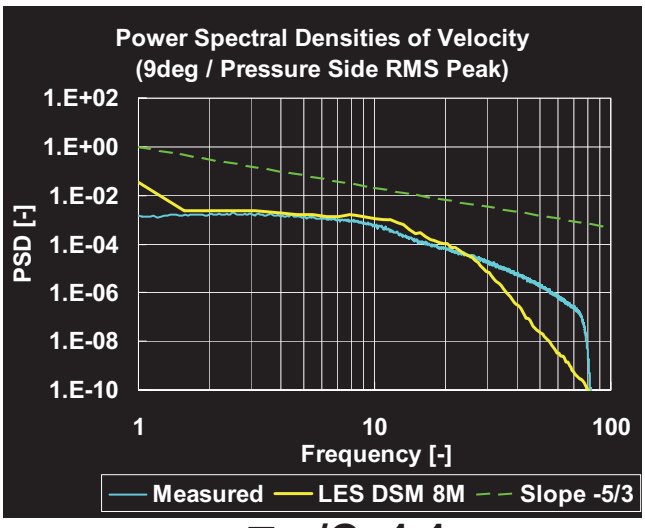
■ **Re = 2.5 x 10^6**
(U_0=50m/s, C=0.75m)

Comparisons of Frequency Spectra of Velocity Fluctuations in Near Wake

Angle of Attack: 9 degrees, Re = 2.0 x 10^5



■ **x/C=1.1**
(suction side)



■ **x/C=1.1**
(pressure side)

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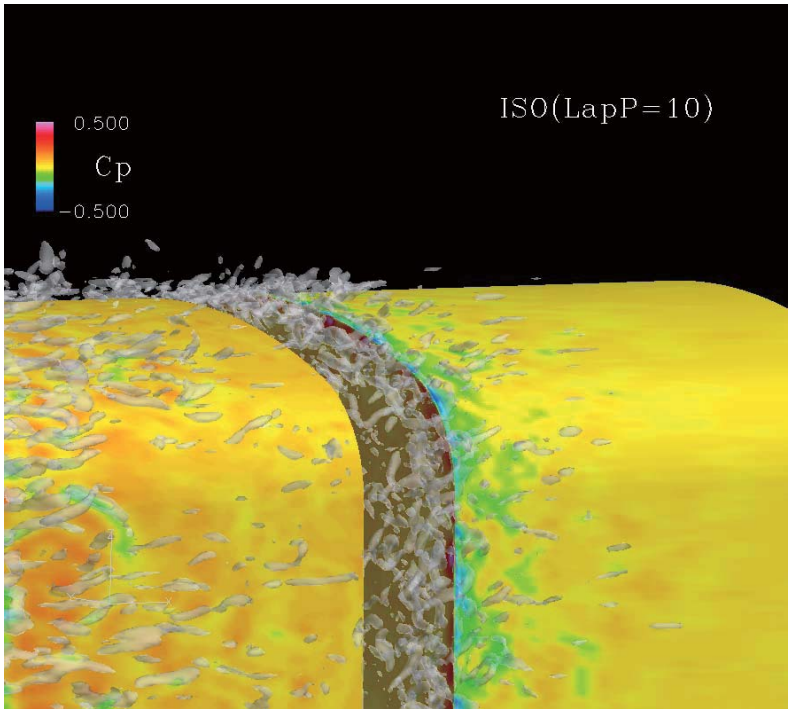
Approaching TBL and Flow in Actual Car Gap



平成21年9月3日

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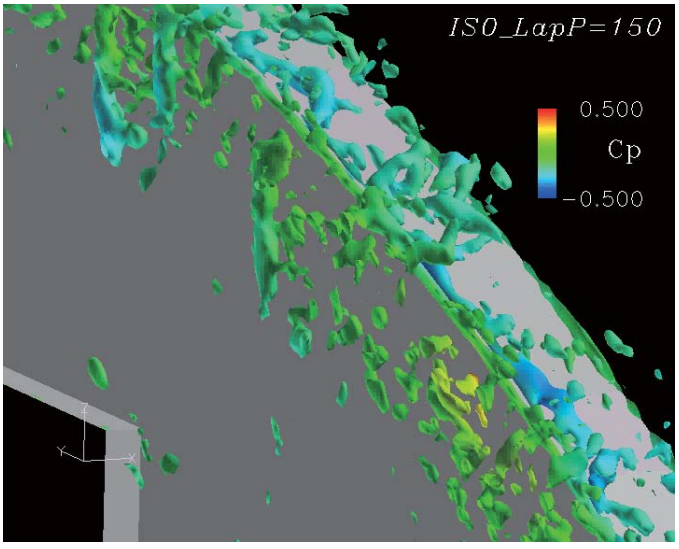
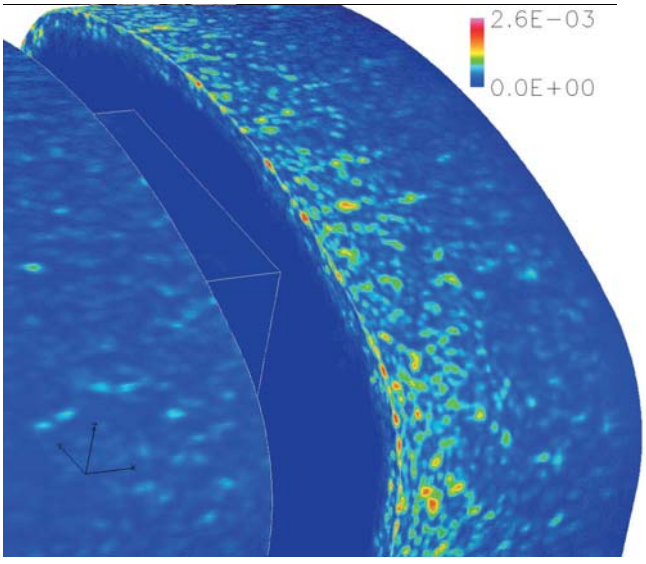
Stretching of Vortices and Acoustical Source on Surface



Stretching of Vortices at the Edge



Aeroacoutsical Sources at 4. 8 Hz

26

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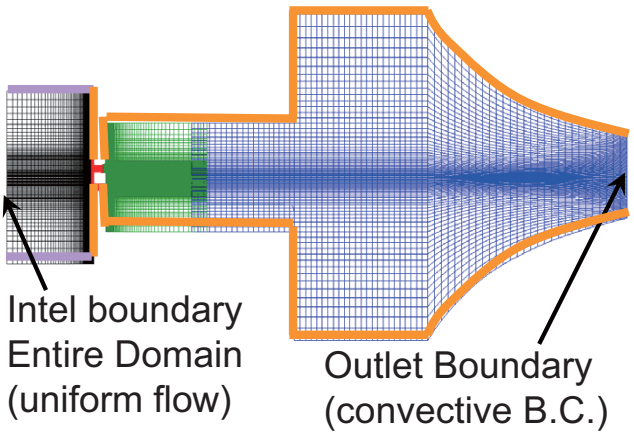
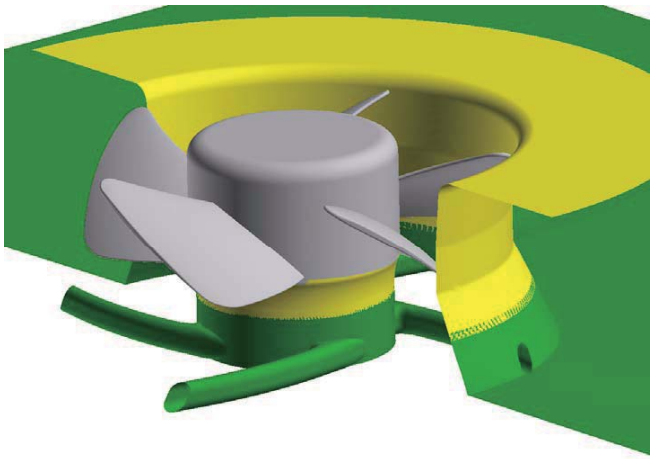
Sound Radiated from a Small Propeller Fan

Computational Model and Boundary Conditions



Entire Domain



Near Fan Blades

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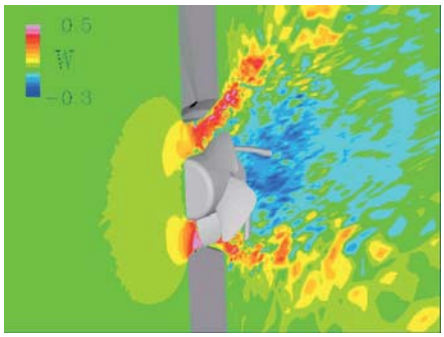
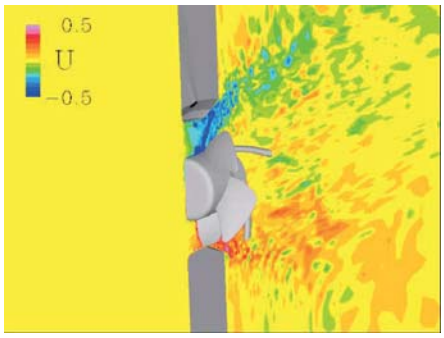
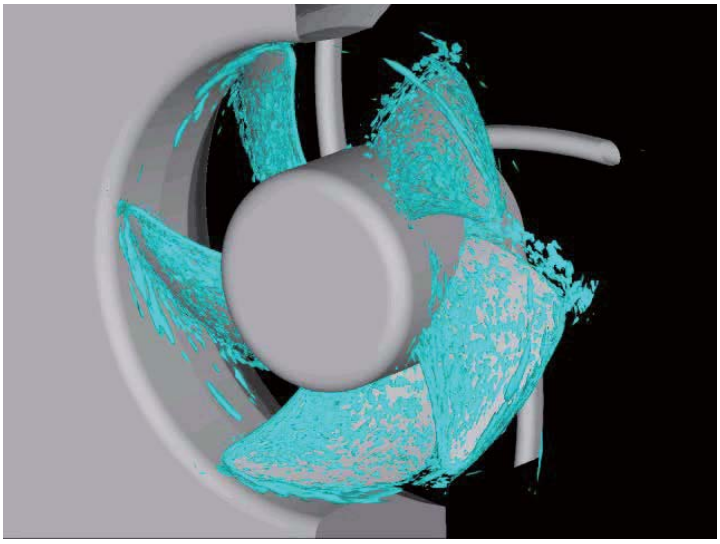
Instantaneous Flow Fields







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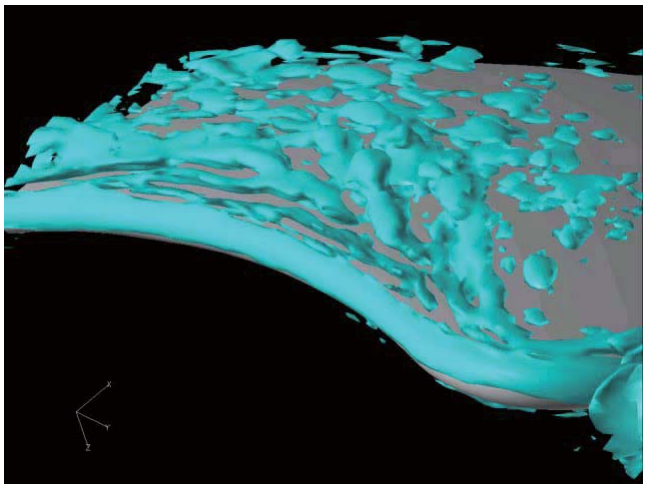
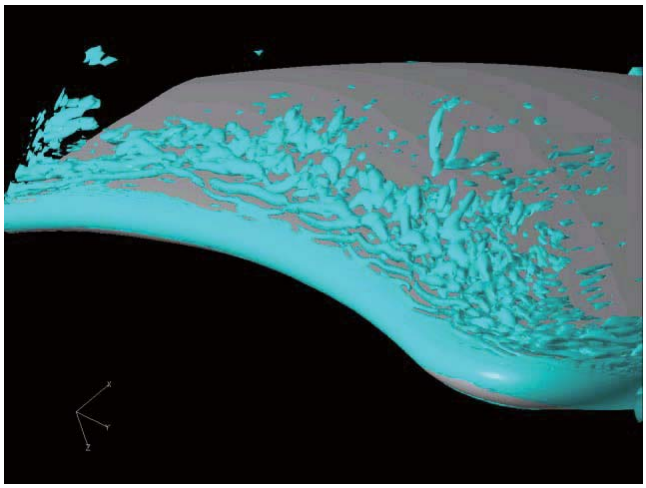
Effects of Grid Resolutions



Coarse Mesh



Fine Mesh

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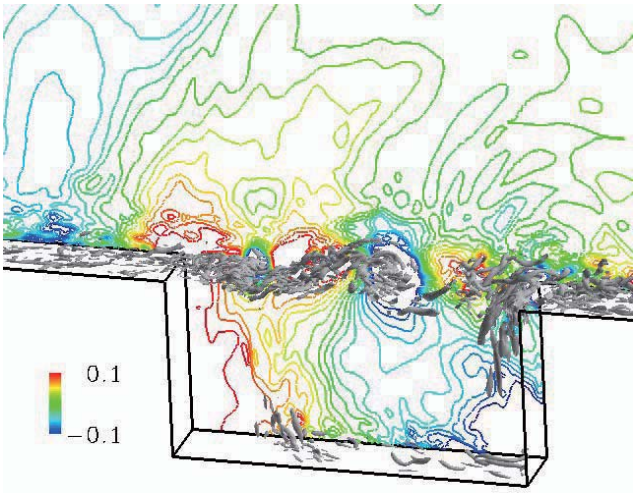
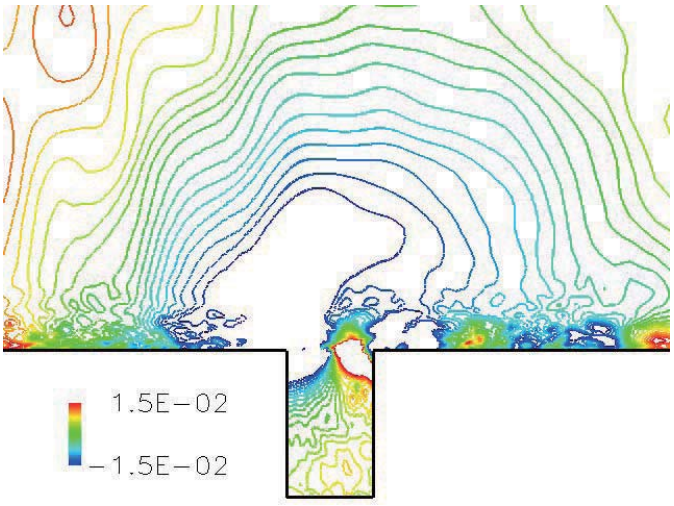
キャビティ音の直接数値解析

■ フィードバック機構の詳細解明





D/*L* = 0.5 (St = 0.8)　　*D*/*L* = 1.7 (St = 0.4)

Perspectives and Future Roles of Measurements

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Summary

■ Numerical Predictions of Aerodynamic Noise

- ➢ will partially replace protoryping and/or model tests up to Reynolds number O(10^6)

■ Future Role of Measurements

- ➢ Provide accurate and detailed data for validating numerical methods
- ➢ Extract Essential Physical Phemomena

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ItoLab.

Flow Visualization in Real and Time Spaces

Takayuki Itoh

Department of Information Sciences
Ochanomizu University

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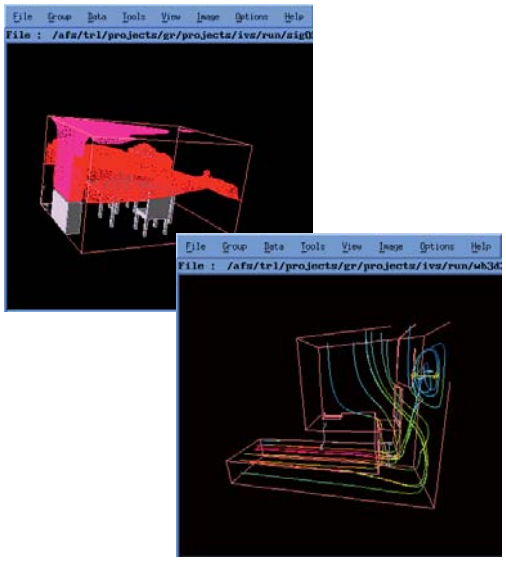
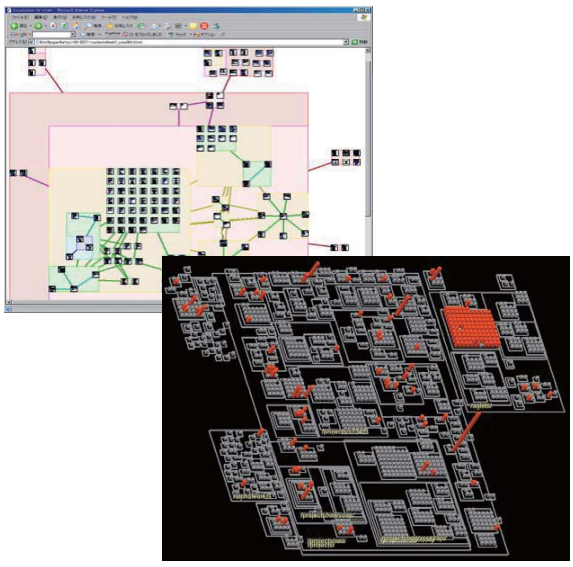
ItoLab.

Various visualization

- Scientific Visualization
  - Mainly scientific data
  - Mainly physical spaces
- Information Visualization
  - Various data
  - Mainly non-physical spaces





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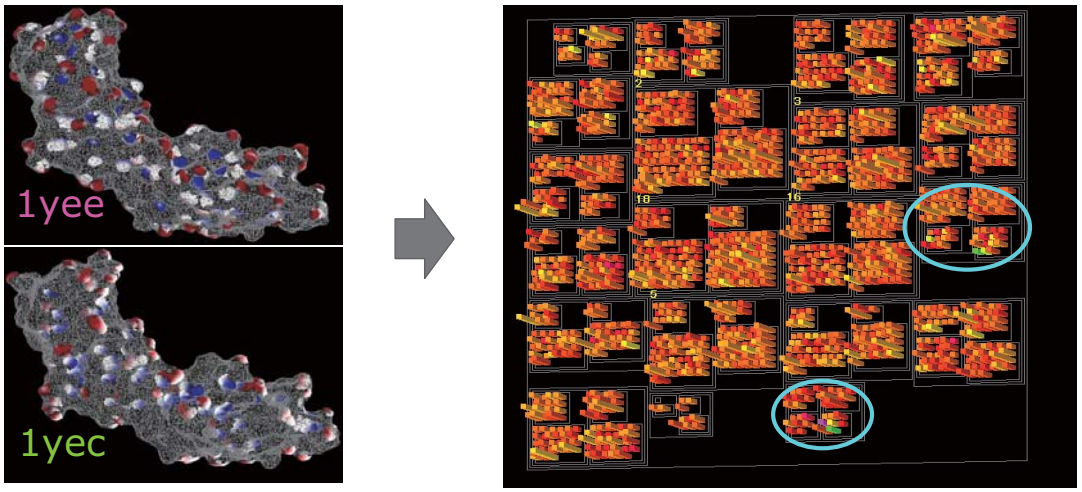
ItoLab.

Typical topic in Itoh lab.
(1) Protein surface analysis

- Retrieval and comparison of similarly shaped protein surfaces

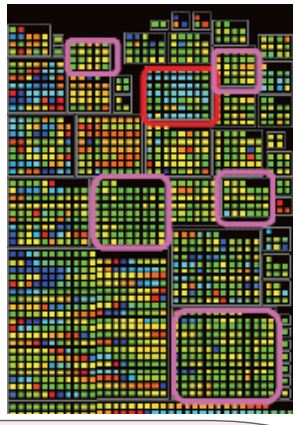
Very similar, but partially different proteins

Chemical properties are also partially different

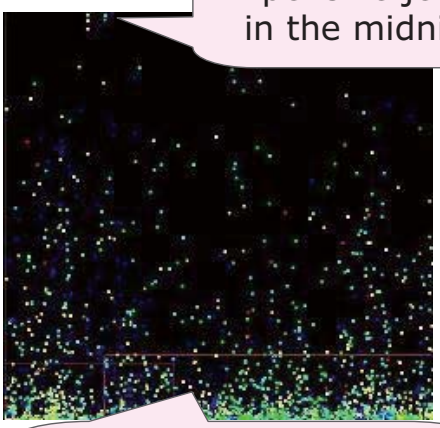


Typical topic in Itoh lab.
(2) Credit card fraud analysis

- Discovery of trend and correlation among attributes of malicious transactions



Many of transportation-related frauds are in the morning



Expensive jewelry in the midnight

Many abnormal refunds from specific shops

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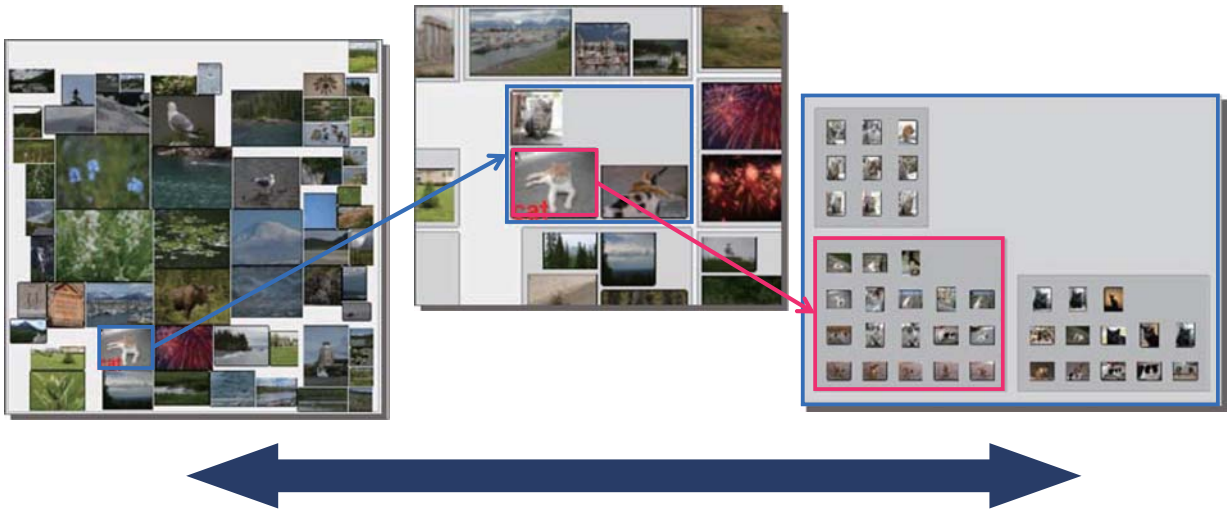
ItoLab.

Typical topic in Itoh lab.

(3) Browser for many images

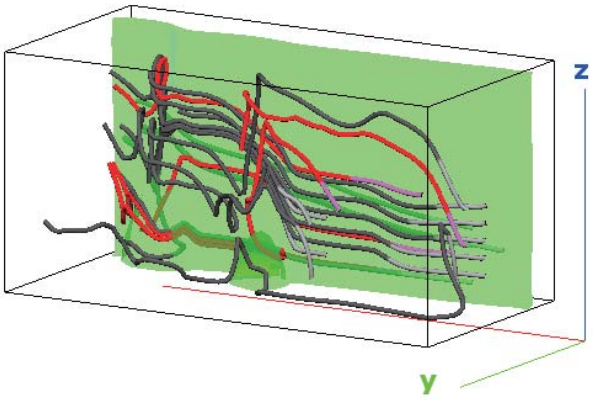
- Zooming user interface for clusters of images

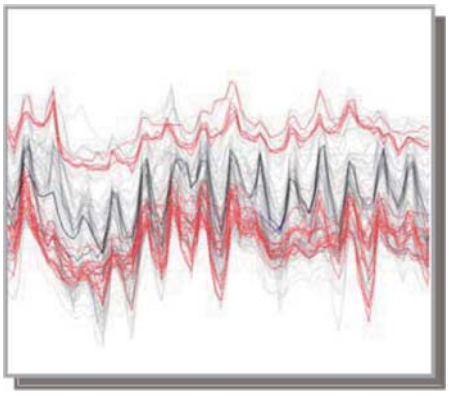


ItoLab.

Today's topic

- Real space visualization
  - Integrated scalar & vector visualization
- Time space visualization
  - Level-of-detail control for polyline charts





- Towards integrated EFD/CFD visualization

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ItoLab.

Let me go to other charts ...

A Streamline Selection Technique for Integrated Scalar & Vector Visualization

Takayuki Itoh, Shiho Furuya

Ochanomizu University

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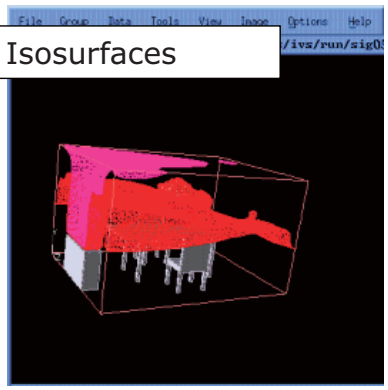
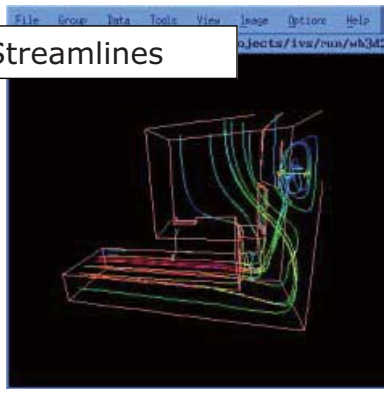
Background
… Scalar and vector visualization

Scalar field	Vector field
2D ■ Contour lines 3D ■ Isosurface ■ Volume rendering	2D ■ Arrow plots 3D ■ Streamline ■ Line integral convolution

Isosurfaces



Streamlines

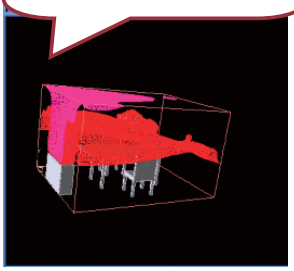


Background
Integrated scalar & vector data

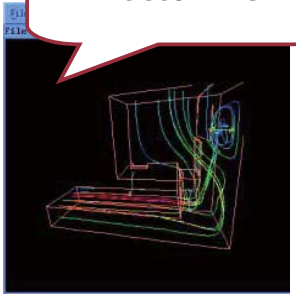
Ex. Weather simulation data
- Pressure, temperature, air flow…etc

Needs of integrated visualization to understand relationships between scalar and vector fields

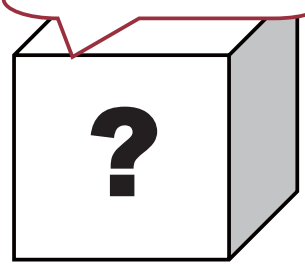
Scalar vis.



Vector vis.



Integrated



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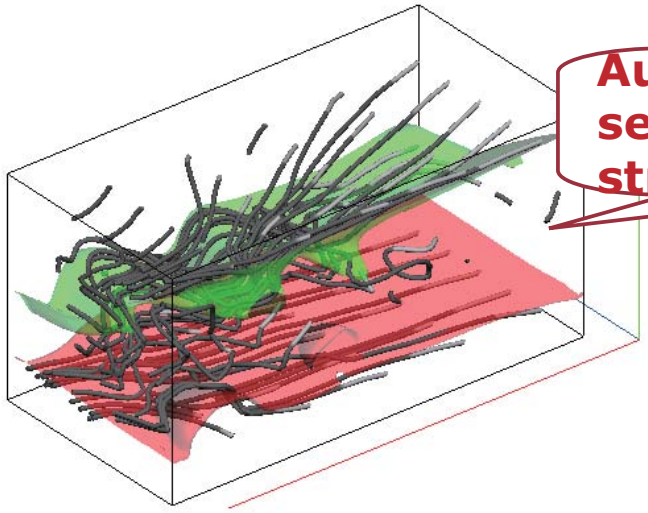
Target of this study:

Integrated 3D scalar & vector visualization

- Isosurfaces for scalar
- Streamlines for vector



Processing flow

STEP1: Generate many streamlines temporarily, and calculate their information entropy

↓

STEP2: Check if they go through critical points

↓

STEP3: Check if they are occluded by isosurfaces

↓

Select the good streamlines according to the 3-step evaluation

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Processing flow

STEP1: Generate many streamlines temporarily, and calculate their information entropy

STEP2: Check if they go through critical points

STEP3: Check if they are occluded by isosurfaces

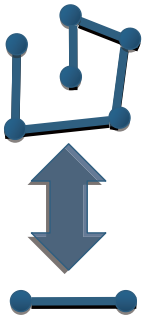
Select the good streamlines
according to the 3-step evaluation

STEP1: Information entropy

$$E = -\frac{1}{\log_2(m+1)} \sum_{j=0}^{m} \frac{D_j}{L} \log_2 \frac{D_j}{L}$$

L : Length of a streamline in 3D space
D_j : Length of j-th segment in 2D display space
m : Number of segments of the streamline

- Calculation for each streamline
- Higher information entropy
  = Uniformly long segments in 2D display space
- **To select "*informative*" streamlines**



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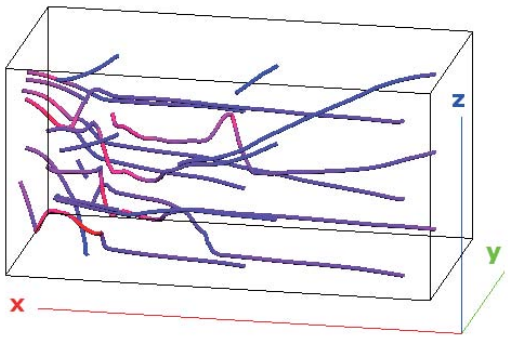
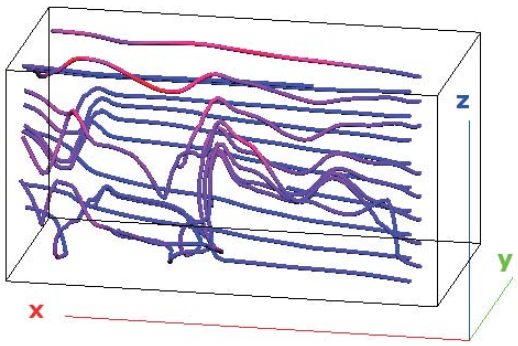
STEP1: Information Entropy

Streamlines just uniformly generated



- Too short, less informative

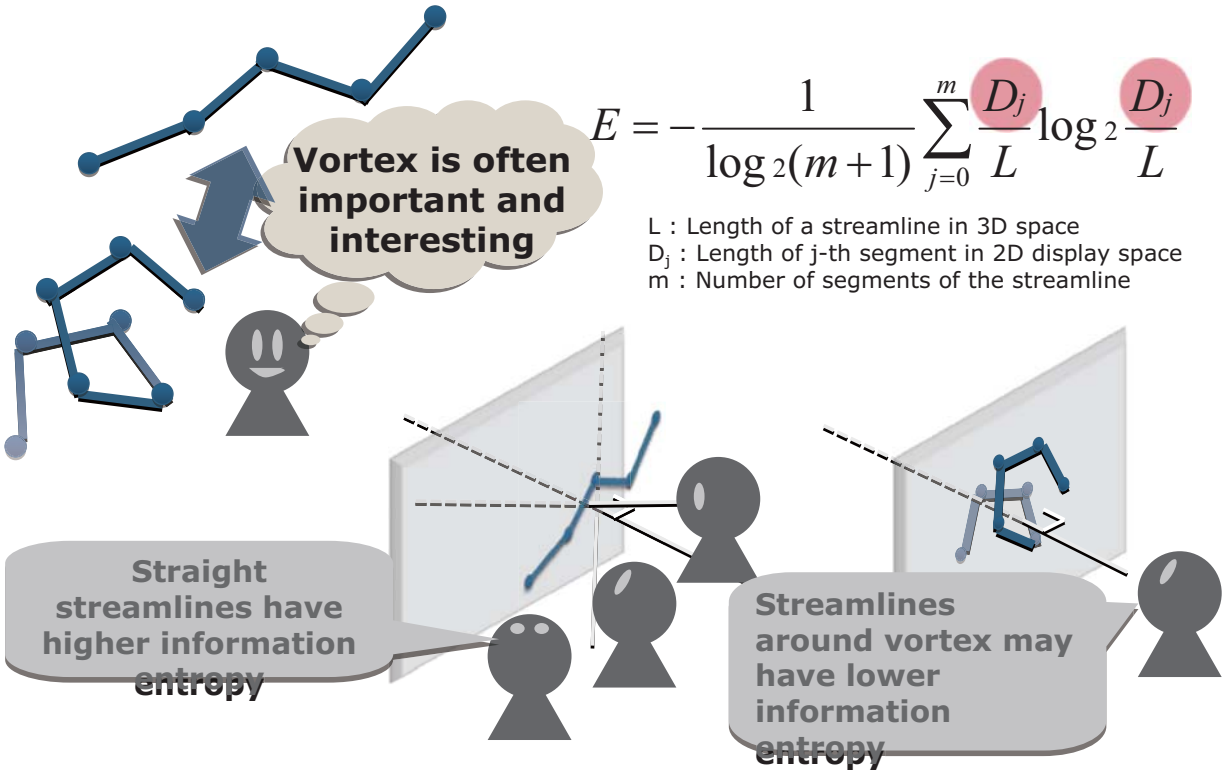
Streamline selected by information entropy



- Globally visualized by informative streamlines

Air flow by a weather simulation

STEP1: Information Entropy



$$E = -\frac{1}{\log_2(m+1)} \sum_{j=0}^{m} \frac{D_j}{L} \log_2 \frac{D_j}{L}$$

L : Length of a streamline in 3D space
D_j : Length of j-th segment in 2D display space
m : Number of segments of the streamline

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Processing flow

STEP1: Generate many streamlines temporarily, and calculate their information entropy

STEP2: Check if they go through critical points

STEP3: Check if they are occluded by isosurfaces

Select the good streamlines according to the 3-step evaluation

STEP2: Critical points

- Where is a critical point?
  - Vector: velocity is zero
  - Scalar: local minimum/maximum, saddle
- The technique divides streamlines
  - Going around critical points
  - Others

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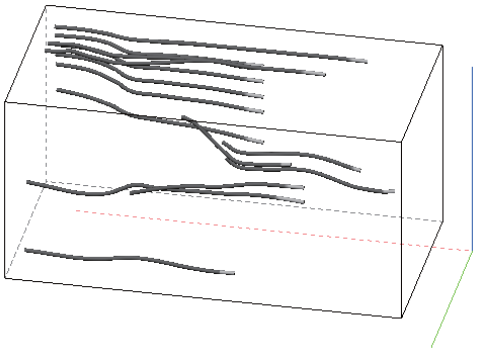
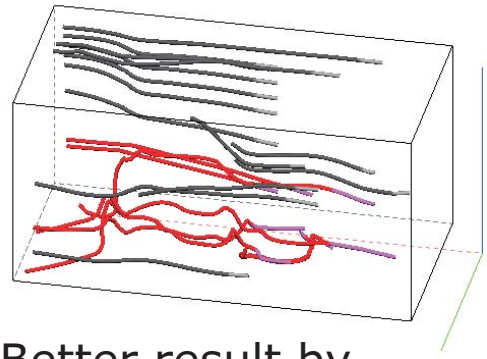
STEP2: Critical points

WITHOUT STEP2	WITH STEP2
	
▫ Local interesting features around critical points are missing	▫ Better result by aggressively selecting streamlines around critical points

Red: around critical points Black: others

Processing flow

STEP1: Generate many streamlines temporarily, and calculate their information entropy

STEP2: Check if they go through critical points

STEP3: Check if they are occluded by isosurfaces

Select the good streamlines according to the 3-step evaluation

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STEP3: Occlusion by isosurfaces

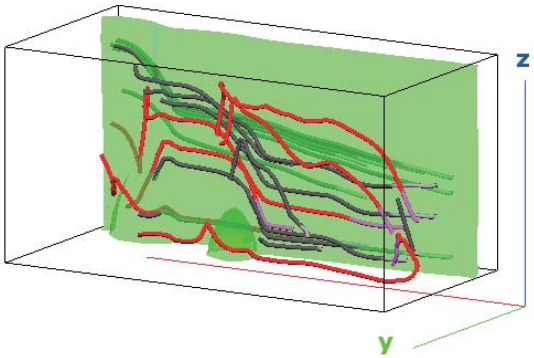
- Visually unnatural if many streamlines “behind” isosurfaces are selected
- Aggressively select “near” streamlines
  - By assigning penalties to occluded streamlines

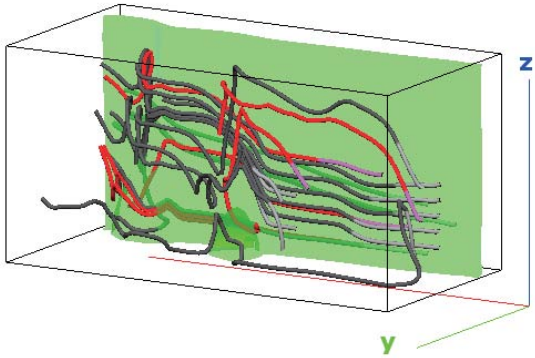
$$E' = (1 - \frac{m}{M})E + (\frac{m}{M})(1 - \alpha)E$$

New entropy: E’
Original entropy :E
Num. of segments :M
Num. of occluded segments: m
Opacity of isosurface: α

STEP3: Occlusion by isosurfaces

WITHOUT STEP3	WITH STEP3





- Many invisible streamlines behind the isosurface
- More number of visible streamlines are selected

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Conclusion & Future works

- Conclusion
  - Automated streamline selection for integrated scalar and vector visualization
    - Higher information entropy
    - Around critical points
    - Less occlusion by isosurfaces
- Future works
  - Selection of important critical points
  - Seamless visualization of time-varying data

FRUITS TIME: AN INTERACTIVE VISUALIZATION TECHNIQUE FOR TIME-VARYING DATA

Takayuki ITOH, Yumiko UCHIDA
Ochanomizu University

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TARGET: LARGE TIME-VARYING DATA

- Various data in our daily life
  - Stock prices, Weather measurements, Simulation results, etc.

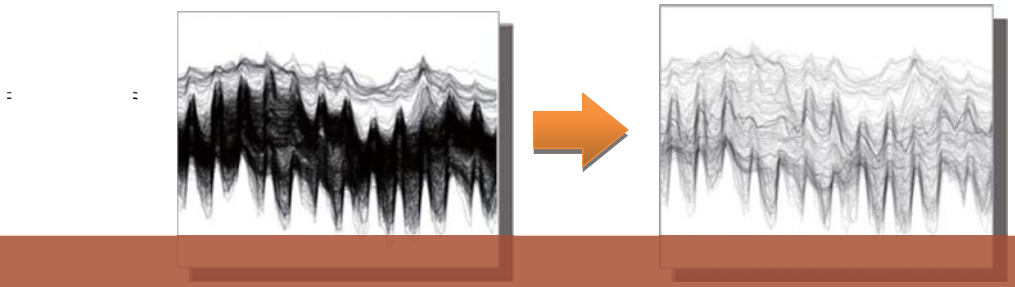
**Difficult to read large time-varying data,
if it is simply drawn as polylines in a single chart space**

Level-of-detail (LOD) control **and** ***interactive query***
for polyline-based large time-varying data visualization

- **Easily discover features from large data**
- **Interactively extract interesting part of the data**

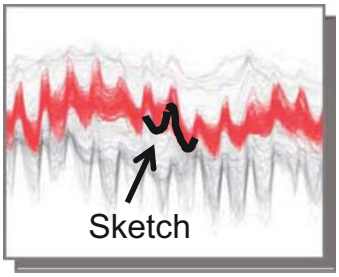
OVERVIEW OF "FRUITS TIME"

- **Level-of-Detail Control of Polylines**
  - Cluster similarly-shaped polylines, and remain representative polylines



- **Overview while finding local interesting features**
- **Interactive resetting of level-of-detail control**

- **Sketch-based query of polylines**
  - Highlight representative polylines
  - Highlight non-representative polylines



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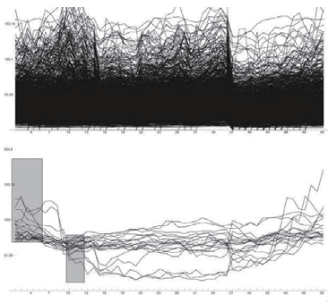
RELATED WORKS

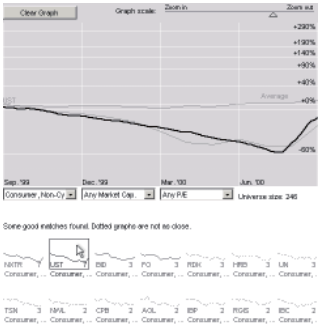
- Problems for visualizing large amount of time-varying data
  - Cluttering among polylines
  - Missing interesting features

Improved techniques for polyline-based visualization



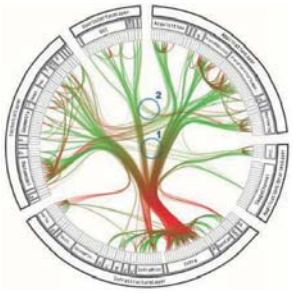
Range-based query of time-varying data

[H. Hochheiser 2004]



Sketch-based query of time-varying data

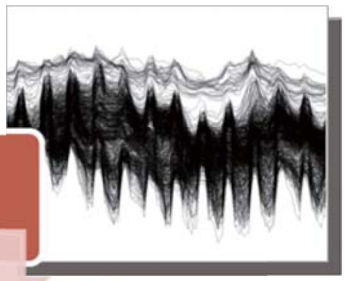
[M. Wattenberg 2001]



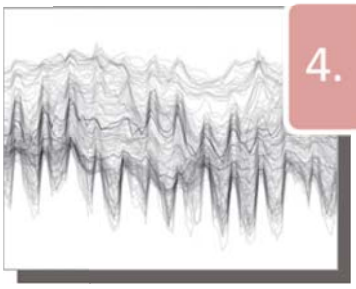
Hierarchical edge bundling

[D. Holten 2006]

FEATURE 1: LEVEL-OF-DETAIL CONTROL



1. Sampling & Quantization
2. Clustering
3. Representative selection
4. Display representatives



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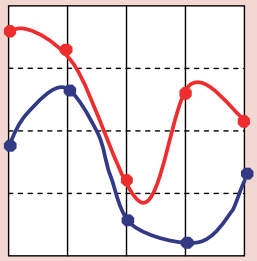
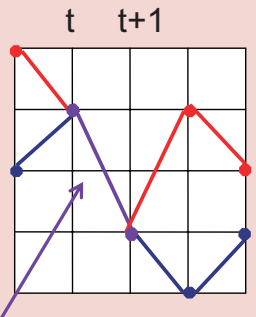
SAMPLING, QUANTIZATION, AND GROUPING

1. Sample time steps



2. Quantize values
3. Group polylines



Belong to the same group if:
quantized values at t-th and (t+1)-th values are equal

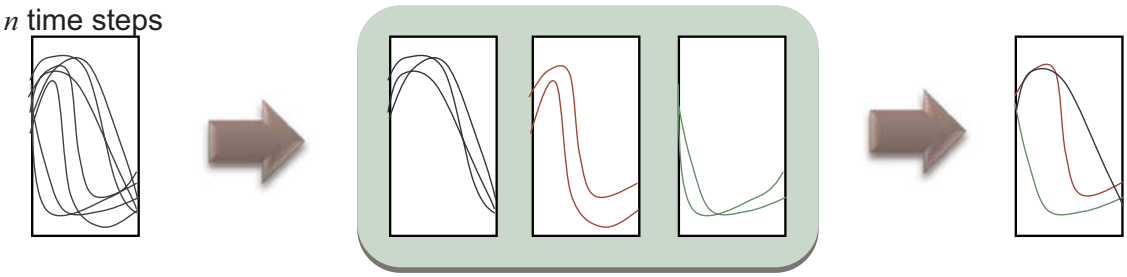
CLUSTERING AND REPRESENTATIVE SELECTION

Clustering of polylines in the groups based on original shapes

- n time steps in a grid subspace
- n-dimensional vector from the y-coordinate values
- Clustering of the n-dimensional vectors

Representative selection for each cluster

- Select the polyline that is closest to the center of a cluster
- Level-of-detail control by displaying only representative polylines
  - Adjust the opacity of the polylines based on numbers of polylines in the clusters



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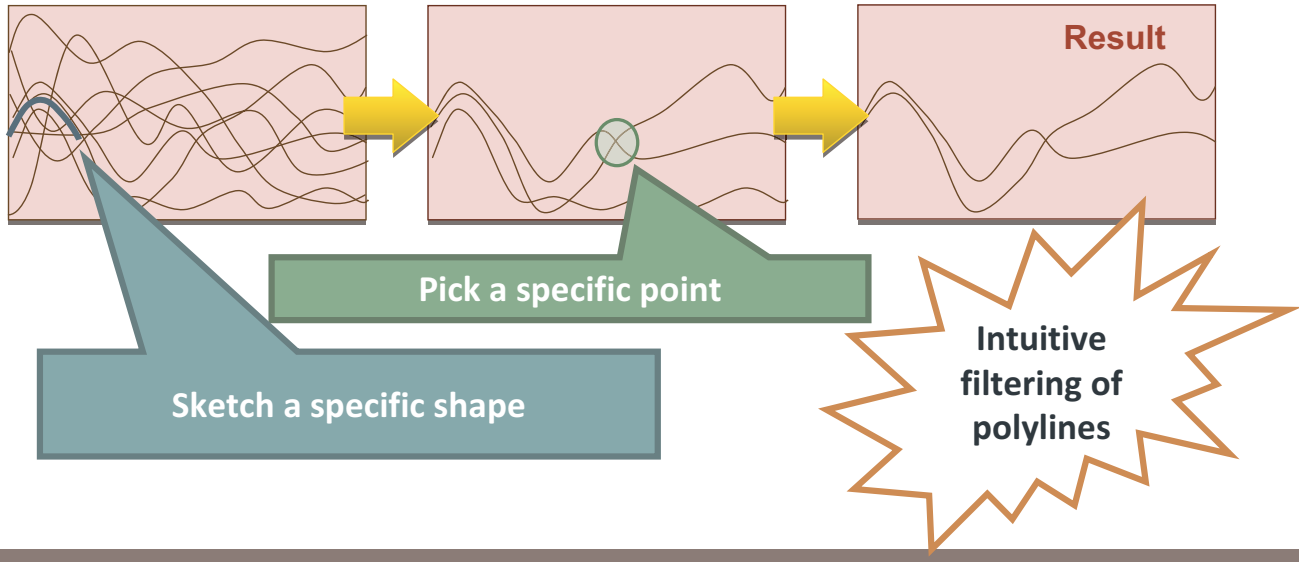
FEATURE 2: SKETCH-BASED QUERY INTERFACE

- Extract specific polylines which drastically change at specific time

Shape-based query system is required

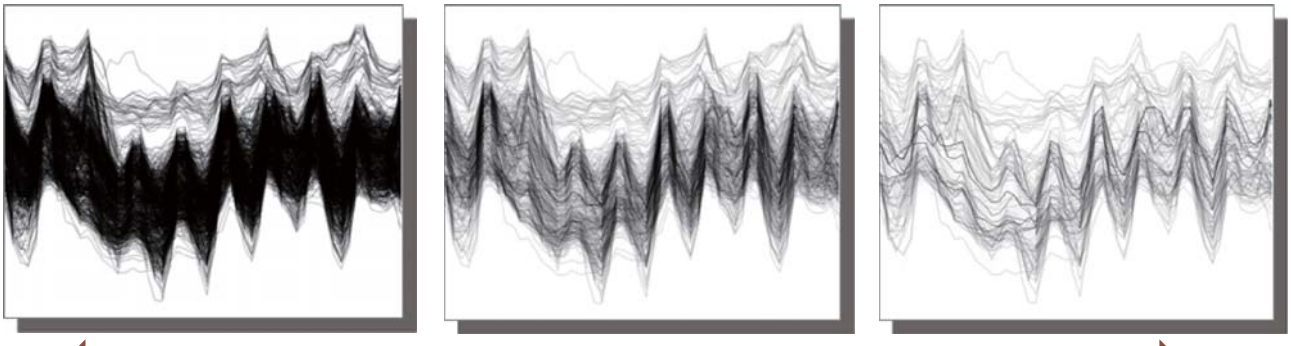
Interactive query & filtering of polylines by:
- Sketching specific shapes
- Picking specific points



RESULT 1: LEVEL-OF-DETAIL CONTROL

- Interactive control of resolution of sampling/quantization with GUI

Ex: Temperature measurement at various places in Japan



More (916) **Number of polylines** Few (273)

Flexible control of level-of-detail

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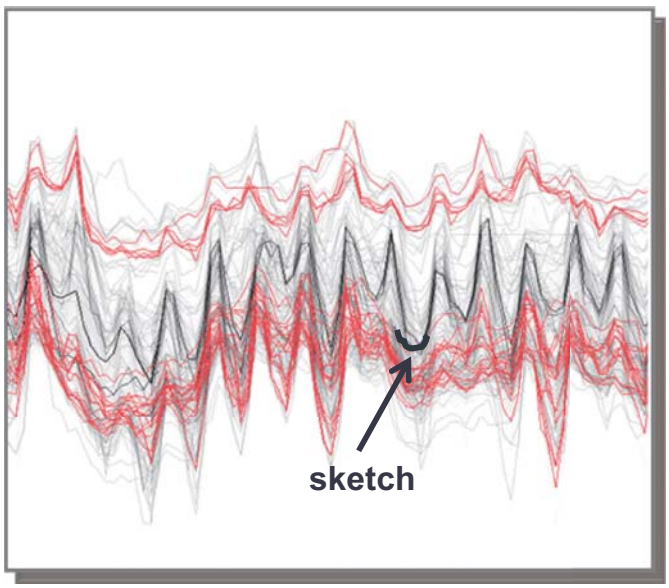
RESULT 2: SKETCH INTERFACE (MOVIE)

- Filtering by multiple query
- Simultaneous display of multiple query results
- User-specified coloring of the query results

RESULT 3: POSITION-IGNORANT QUERY

- Highlight polylines which
  "similarly-shaped, but away from sketched position"



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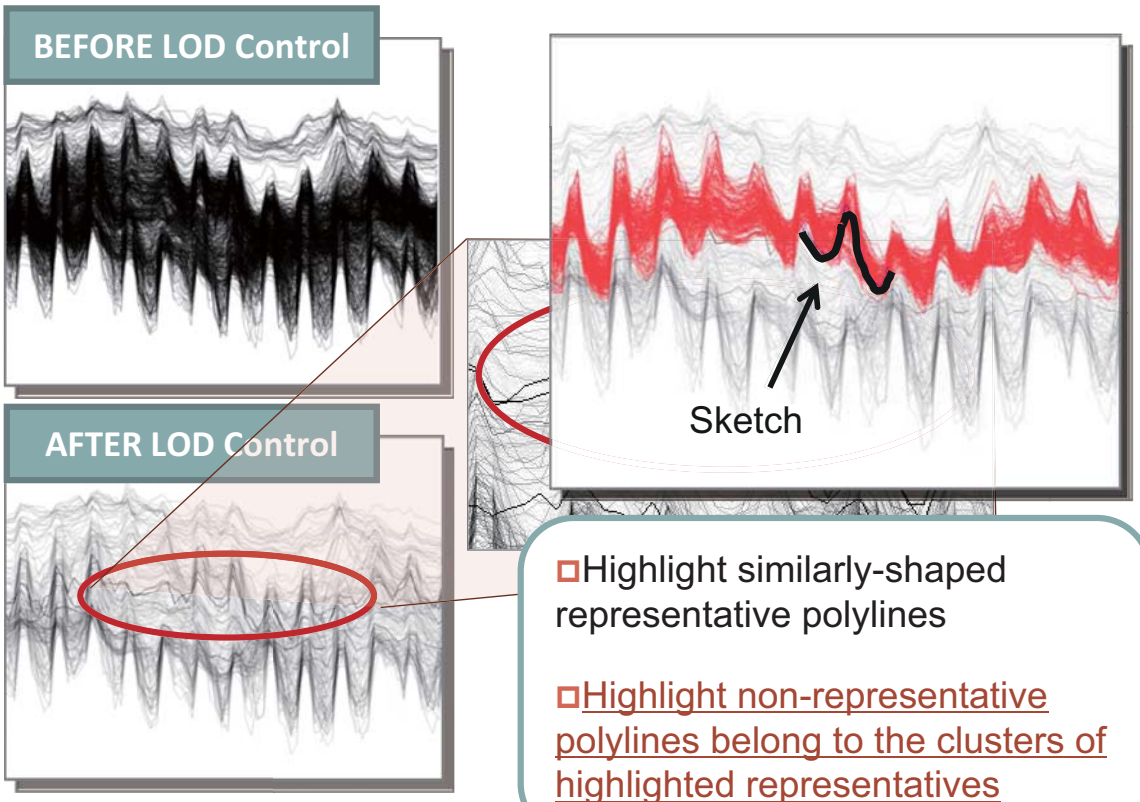
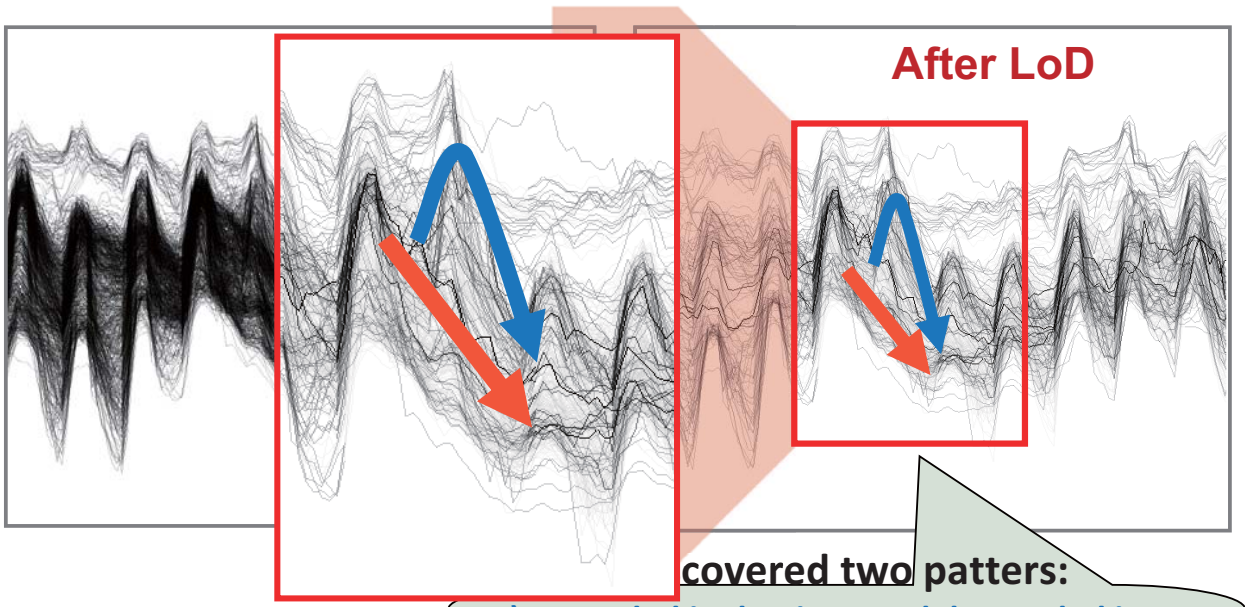
RESULT 4: RESETTING LOD OF HIGHLIGHTING POLYLINES



- Highlight similarly-shaped representative polylines
- Highlight non-representative polylines belong to the clusters of highlighted representatives

APPLICATION TO WEATHER DATA

Temperature measured at 913 points by AMeDAS



covered two patters:

1) Ascended in daytime, and descended in night

2) Not Ascended in daytime, but just descended

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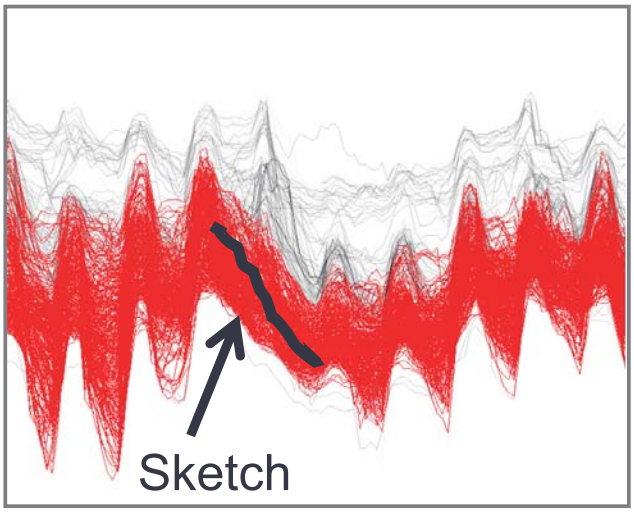
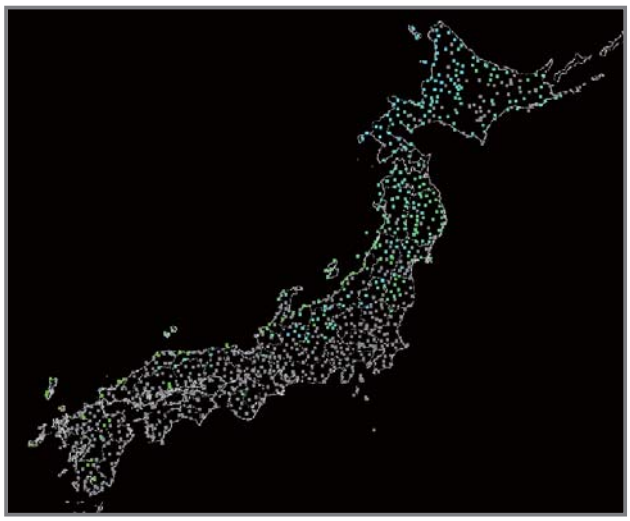
APPLICATION TO WEATHER DATA

- Sketched polylines simply descended
- Highlighted corresponding points on the Japan map



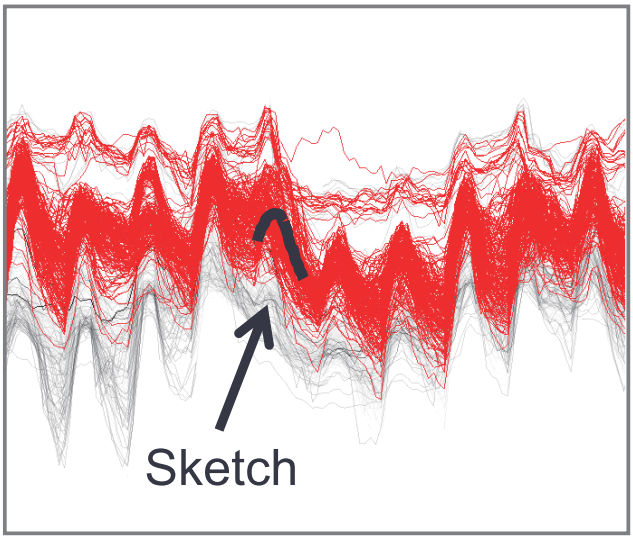


Weather did not ascend in daytime

Bad weather along Japan Sea

APPLICATION TO WEATHER DATA

- Sketched polylines ascended in daytime
- Highlighted corresponding points on the Japan map



Temperature ascended in daytime

Fine weather along Pacific Ocean

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SUMMARY & FUTURE WORKS

- Summary: FRUITS Time
  - A polyline-based time-varying data visualization
  - [Feature 1] LOD Control of polylines
  - [Feature 2] Sketch-based query & partial resetting of LOD
- Future works
  - More case study with real data
  - User evaluation
  - Coordinate view with other visualization techniques
    - Volume visualization? Multi-dimensional visualization?
  - Improvement of clustering process
  - 3D techniques
  - Scalability test

Towards integrated EFD/CFD visualization

- Real space
  - Integrated **EFD-scalar and CFD-vector** visualization
  - Integrated **EFD-vector and CFD-scalar** visualization
  - **Difference-based** visualization between EFD/CFD
- Time space
  - **Similarity/Difference-based** visualization mixing EFD and CFD
  - Sketch interface **from EFD to CFD**
  - Sketch interface **from CFD to EFD**

ItoLab.

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ItoLab.

Conclusion

- Introduction of Itoh lab.
- Topic 1 (Real space):
  Integrated scalar & vector visualization
- Topic 2 (Time space):
  LoD-control for polyline charts
- Towards integrated EFD/CFD visualization

ItoLab.

Future works

- Train successors!!
  - Both works are done by graduating M2 students
- More test cases
- More experiments with EFD
- Scalable algorithm development
  - Our test data is very small
- “Really” integrated system development
  - Real, time, and other visualization techniques
  - EFD, CFD, and other data sources

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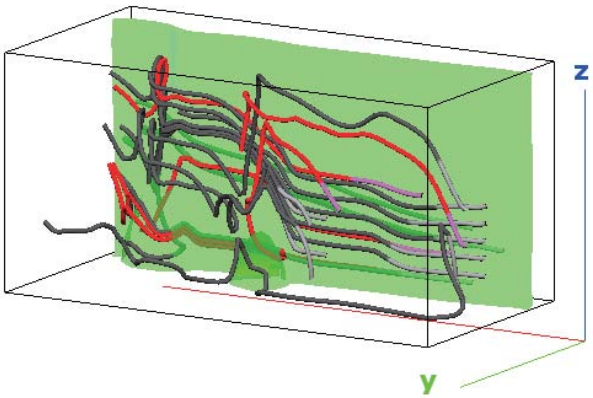
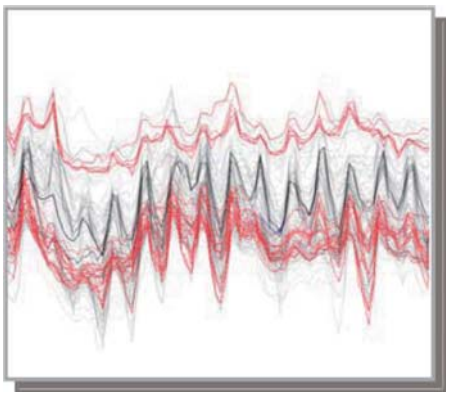
ItoLab.

Thanks you, and any questions?





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Current Status of EFD/CFD Techniques for Road Vehicle Aerodynamics and Development of the Unsteady Aerodynamic Simulator

Makoto. Tsubokura
(Hokkaido Univ.)

Second Workshop on Integration of EFD and CFD

2009.2.24, JAXA

Automotive Development

- Competitive
  - *More than 10 companies in Japan!, around 20 worldwide major.*
- Fast
  - *4 years from the kick-off to the market*
    (About a year shorter than typical Europe or US company).
- Parallel
  - *20 to 30 new models per year in Japan.*
  - *Every company develops several models in parallel.*
- Toward Green Mobility
  - *Major source of CO2 emission*
    (around 20% by vehicle driving in Japan).
  - *Around 50% less for the next 10 years!*

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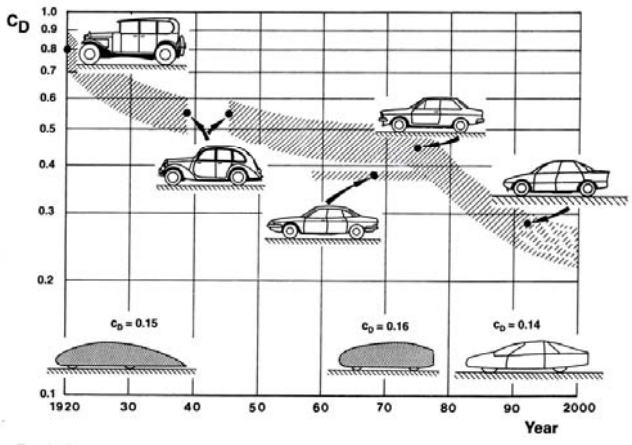
Time history of Cd

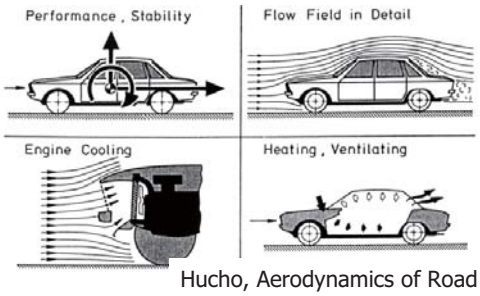


- Still smaller Cd is required.
  - Cd=0.26 to 0.20 can reduce F.C. to 10% less at 100km/h drive.
  - Cd~0.15 in 2030 by an active control or an innovative aerodynamic devices.

Breakthrough is indispensable!

Severe Aerodynamic Development for Road Vehicle

- Complexity
  - *Bluff-body flow……complicated turbulence.*
  - *Interactions among flow, heat and mass, vehicle body…*
    ……complicated physics.
  - *Wide variety of types……complicated geometry.*
- Wide range of problems
  - *Aerodynamic performance, engine cooling, ventilation, aerodynamic noise, soiling*



Hucho, Aerodynamics of Road Vehicle

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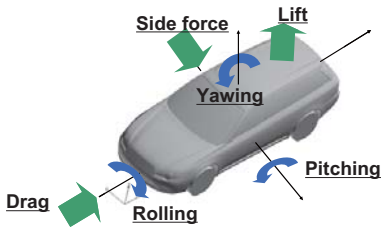
Requirement of Coupled Aerodynamics

- Coupled effects to be considered from the initial stage.

Monotonic analysis



Integral forces and moments

Coupled analysis

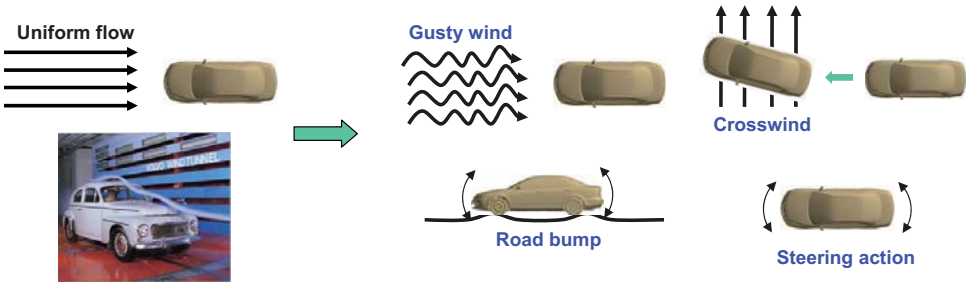
Vehicle body in motion

Thermal management

Aero-acoustic noise

Unsteady Aerodynamic Simulator

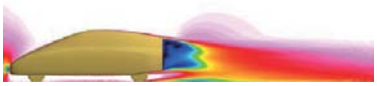
- Unsteady aerodynamics for innovative aerodynamic Design.



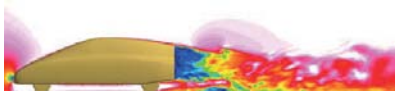
  - To provide additional data which wind-tunnel is difficult to measure.
  - To eliminate the gap between wind-tunnel and on-road measurements!

- Large Eddy Simulation (LES)

Reynolds Averaged Navier-Stokes (RANS)



Large Eddy Simulation (LES)



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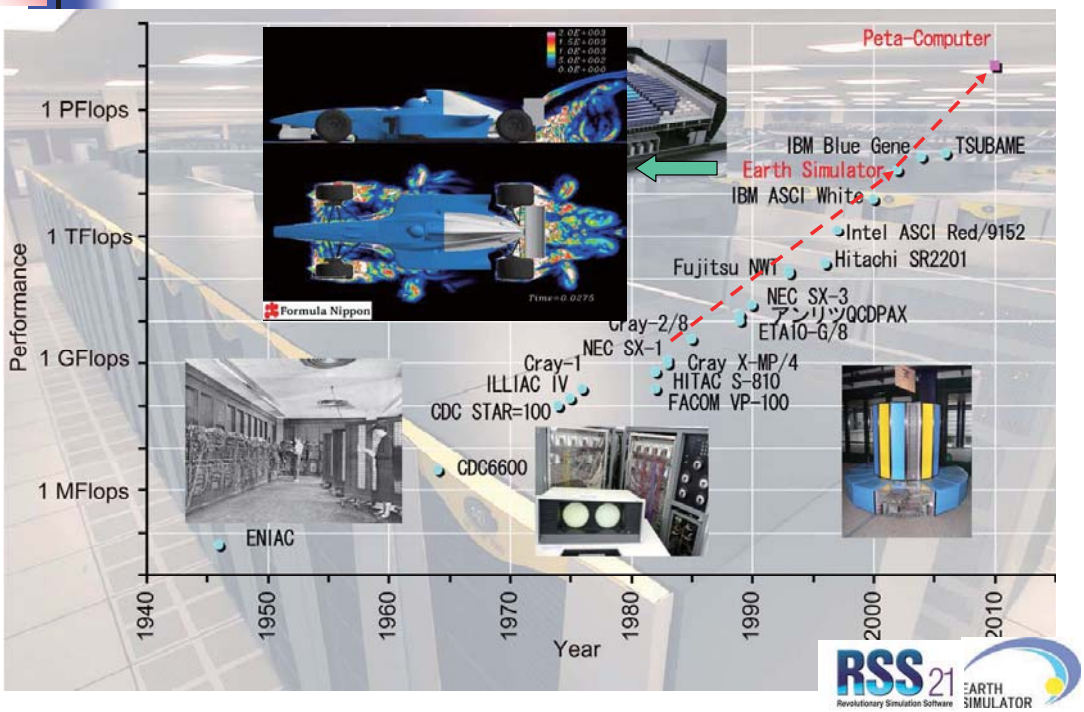
High-Performance Computing for Vehicle Aerodynamics



Numerical Methods
Governing Equations and Physical Models

- Spatially Filtered Navier-Stokes Equation

$$\frac{\partial \overline{u}_i}{\partial x_i} = 0$$

$$\frac{\partial \overline{u}_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\overline{u}_i \overline{u}_i\right) = -\frac{\partial \overline{P}}{\partial x_i} + 2\frac{\partial}{\partial x_j}\left(\nu + \nu_{SGS}\right)\overline{S}_{ij}$$

- Standard Smagorinsky's model

$$\nu_{SGS} = \left(C_s f_s \Delta\right)^2 \sqrt{2\overline{S}_{ij}\overline{S}_{ij}} \qquad C_s = 0.15$$

$$f_s = 1 - \exp\frac{-y^+}{25} \quad \text{:Wall damping function (Van-driest)}$$

$$\Delta = \left(\Delta x_1 \Delta x_2 \Delta x_3\right)^{1/3} \quad \text{:Grid width}$$

- Wall-layer models on the solid surface (Log-law)
  - First grid point with a log-layer (y+~100)

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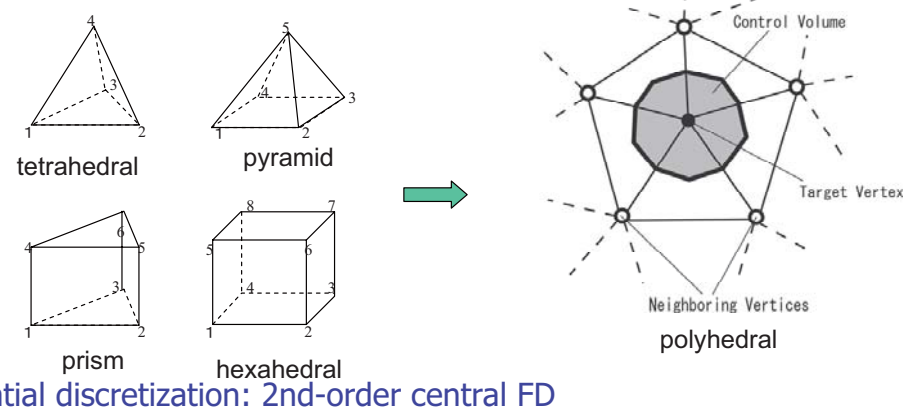
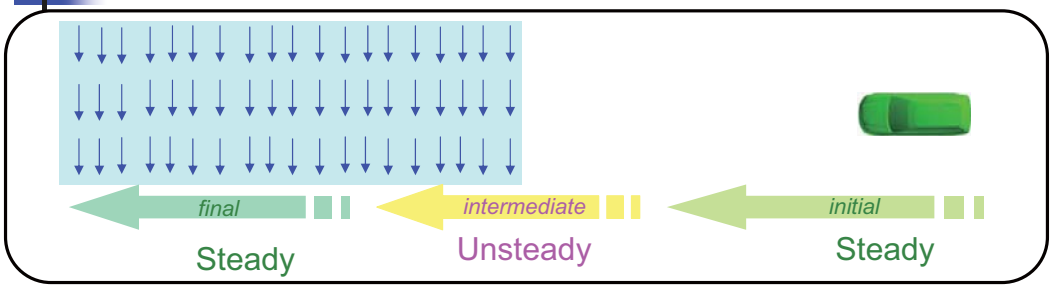
Numerical Methods
Unstructured Finite Volume Methods

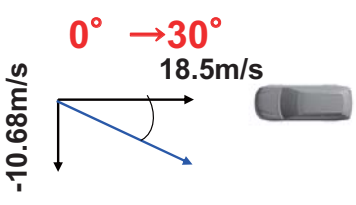
- Vertex-centered Finite Volume Methods

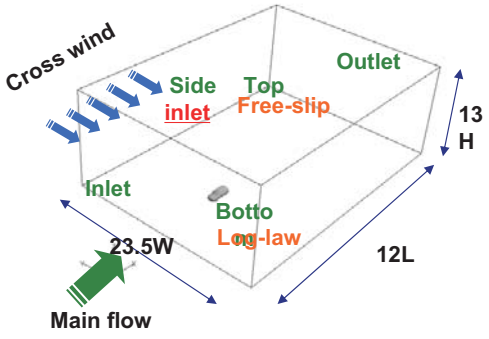


- Spatial discretization: 2nd-order central FD
- Convective Term: Blend of upwind scheme (several %)
- Time Marching Method: 2nd-order Adams-Bashforth
- Pressure-Velocity coupling: SMAC method
- Pressure-Poisson: ICCG
- Front Flow/red

Sudden Crosswind
Problem and Method







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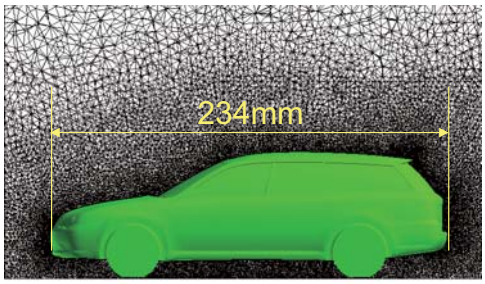
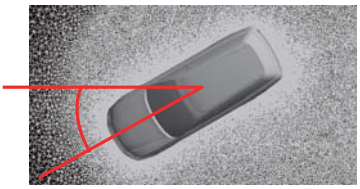
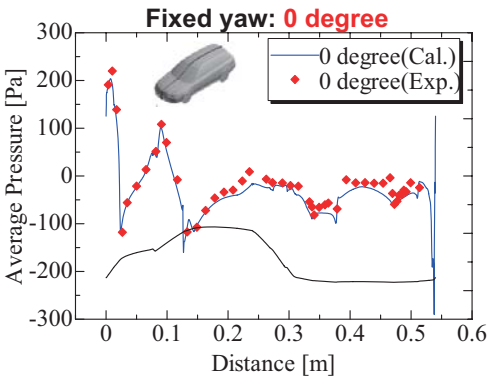
Sudden Crosswind
Target and Validation (Fixed-yaw cases)

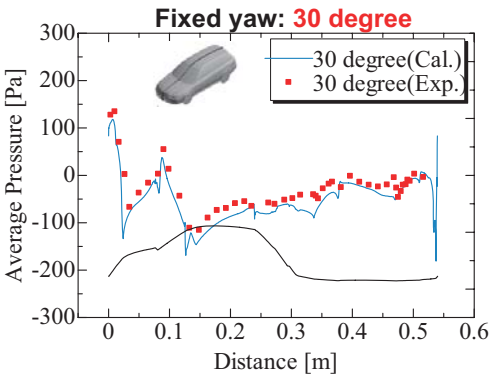
1/20 scale model



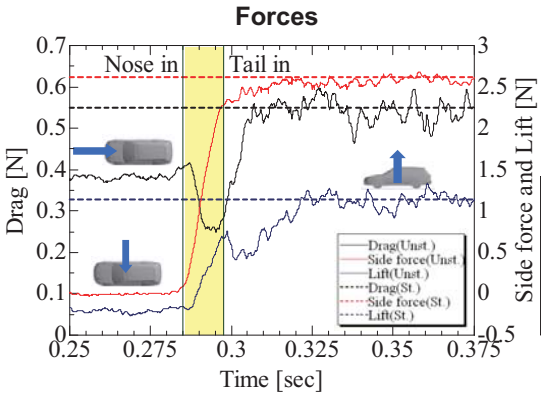


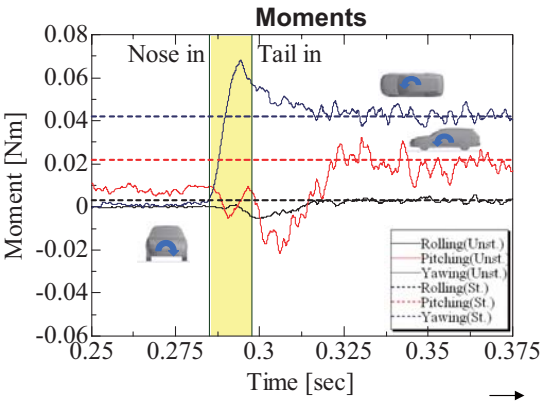
Wind tunnel measurements at Toyama Univ.
Tanaka et al., #20 CFD Symp. A6-2 in Japanese (2005)





Sudden Crosswind
Transient forces and moments





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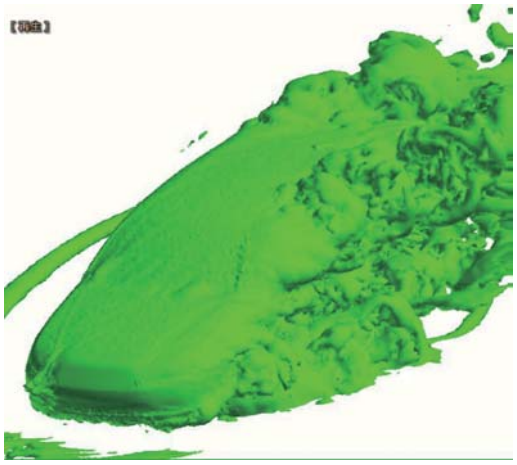
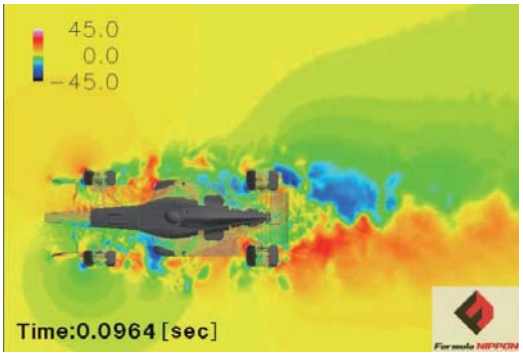
Sudden Crosswind
Eddy Structures around the Vehicle

Before subjected to a crosswind

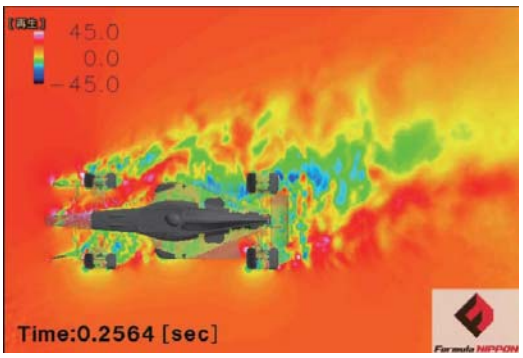


After subjected to a crosswind

Sudden Crosswind
Formula-car case (1)



Before subjected to a crosswind



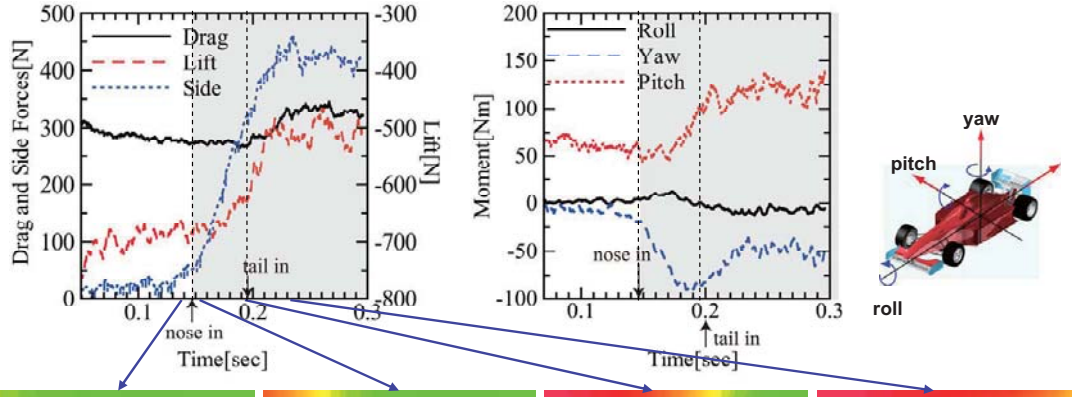
After subjected to a crosswind

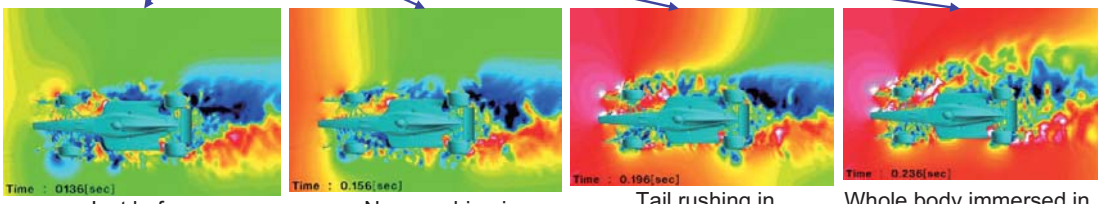
This document is provided by JAXA.

Sudden Crosswind
Formula-car case (2)

Tsubokura et al., SAE Tech. paper No. 2009-01-0007(2009)

- *Overshoot and Undershoot during rushing into crosswind*



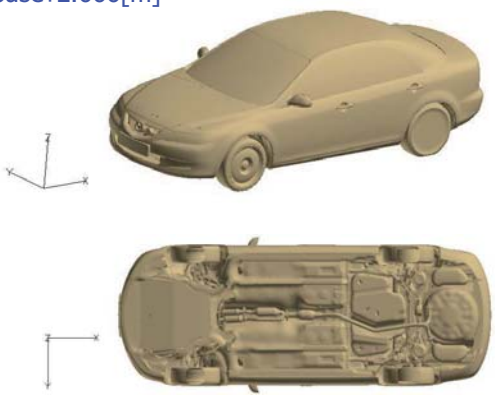


Just before | Nose rushing in | Tail rushing in | Whole body immersed in

Eddy Structures
Target and Experimental Setup

Full-scale model with detailed geometry

length(L) : 4.670[m]
width(W) : 1.954[m]
hight(H) : 1.594[m]
wheel base : 2.666[m]



•Grids

type : tetrahedron
nodes : 6,579,897
elements : 37,870,527

Tsubokura et al., Computers & Fluids, vol.38, 981-990(2009)

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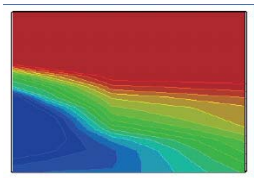
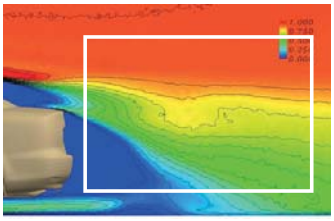
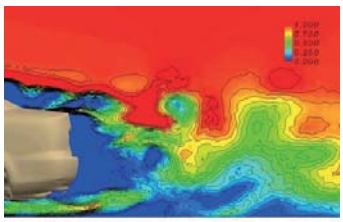
Eddy Structures
Wake Structures (total pressure distribution)

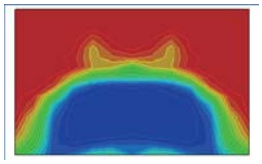


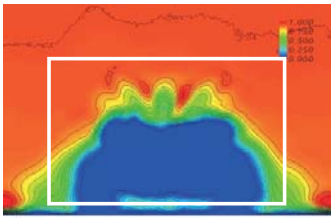
Experiments

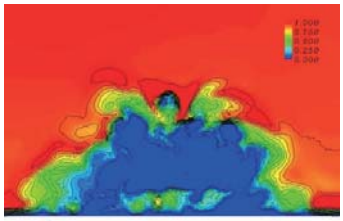




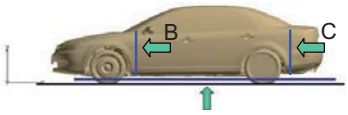
Present LES



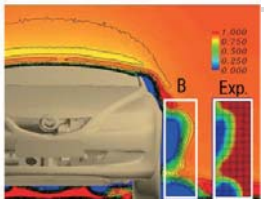


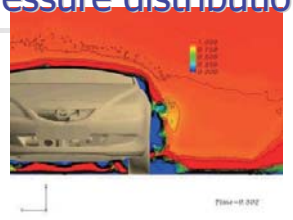


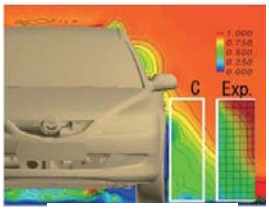
Eddy Structures
Side and Underbody Structures (total pressure distribution)

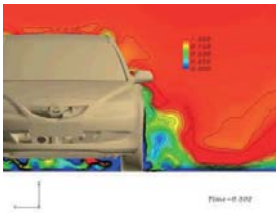


XY-section at 100mm
above the ground



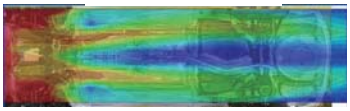


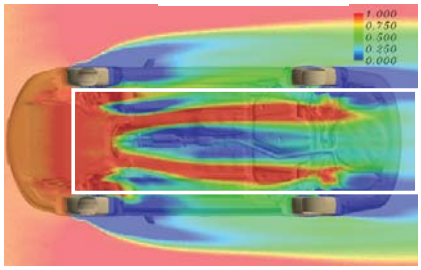


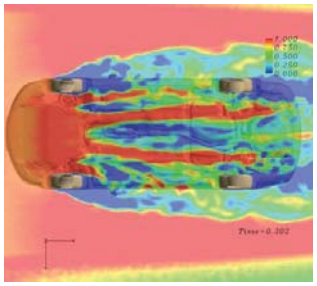


Present LES

Experiments







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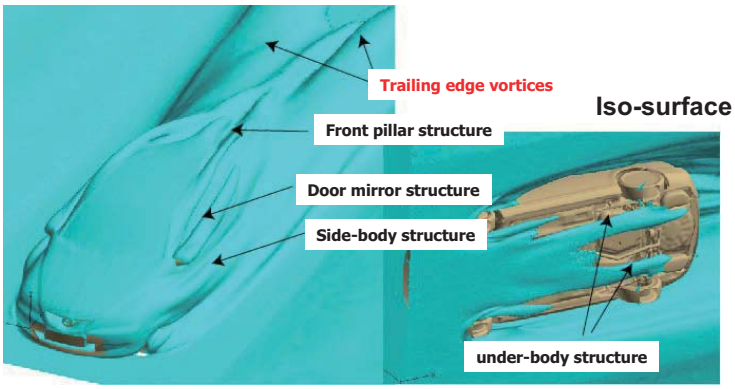
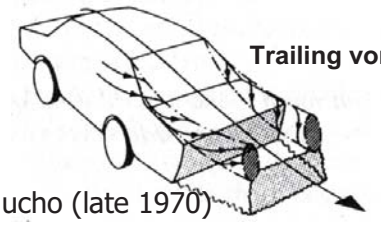
Eddy Structures
Schematics of Overall Structures around the Vehicle





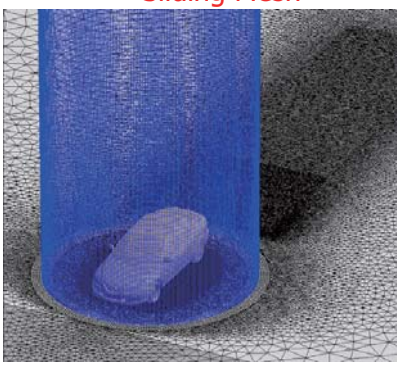
Hucho (late 1970)

Several vortices appear, which rotate like gearwheels engaging each other!

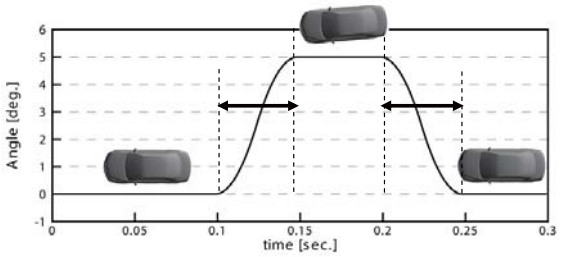
Dynamic Yaw-angle Motion
Target

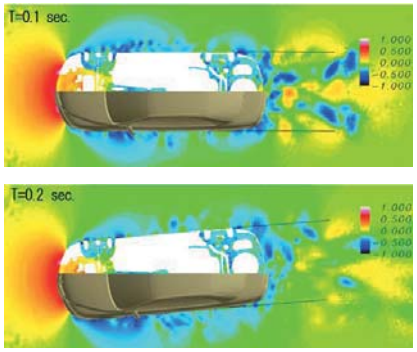
- Vehicle in yaw motion

Sliding Mesh



•Grids
type :tetra+hexa hybrid
nodes : 7,229,633
elements: 39,285,753





Snapshots of pressure distribution

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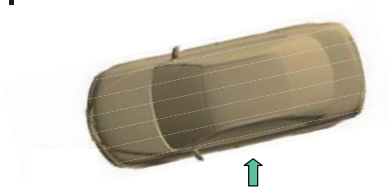
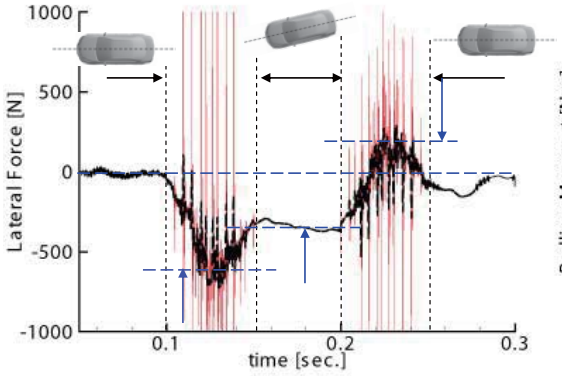
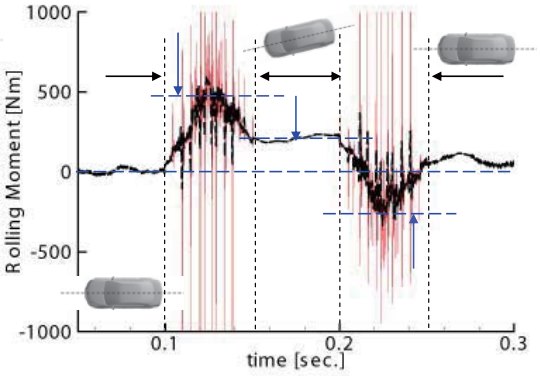
Dynamic Yaw-angle Motion
Transient Force and Moment



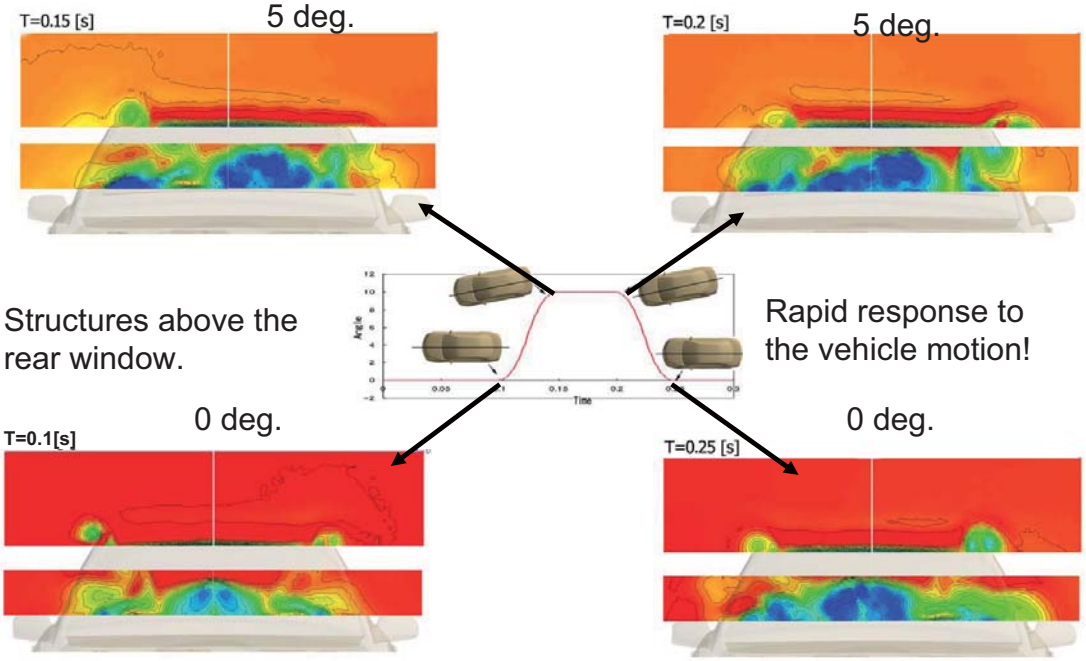
Lateral Force (Y-direction)



Rolling Moment (X-axis)

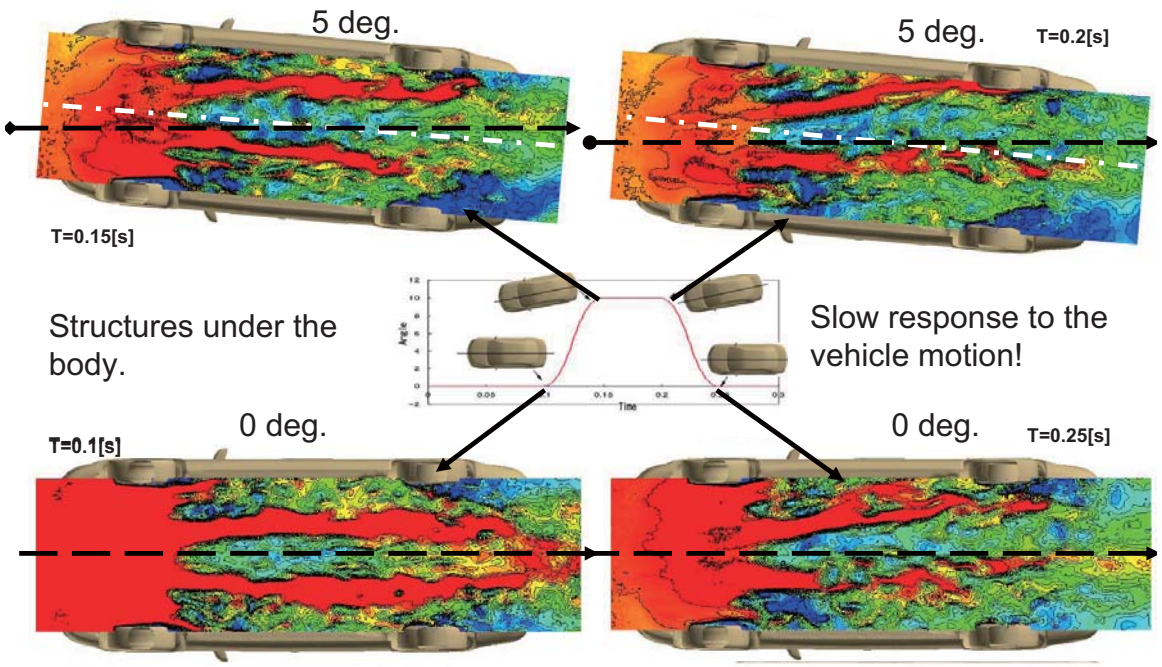


Dynamic Yaw-angle Motion
Time Response of Flow Structures



This document is provided by JAXA.

Dynamic Yaw-angle Motion
Time Response of Flow Structures

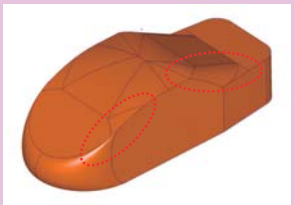


Dynamic Pitch-angle Motion
High-Speed Stability

Nakashima et al., SAE Tech. paper No. 2009-01-0006(2009)

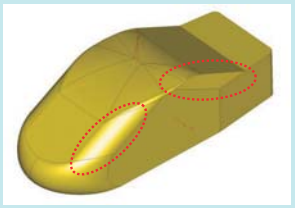
- Two simplified models with different pillar shape.
  - Type A: Unstable
  - Type B: Stable
  - L:210mm x W:80mm x H:65mm

Type A



Edged front-pillar
Rounded rear-pillar

Type B



Rounded front-pillar
Edged rear-pillar

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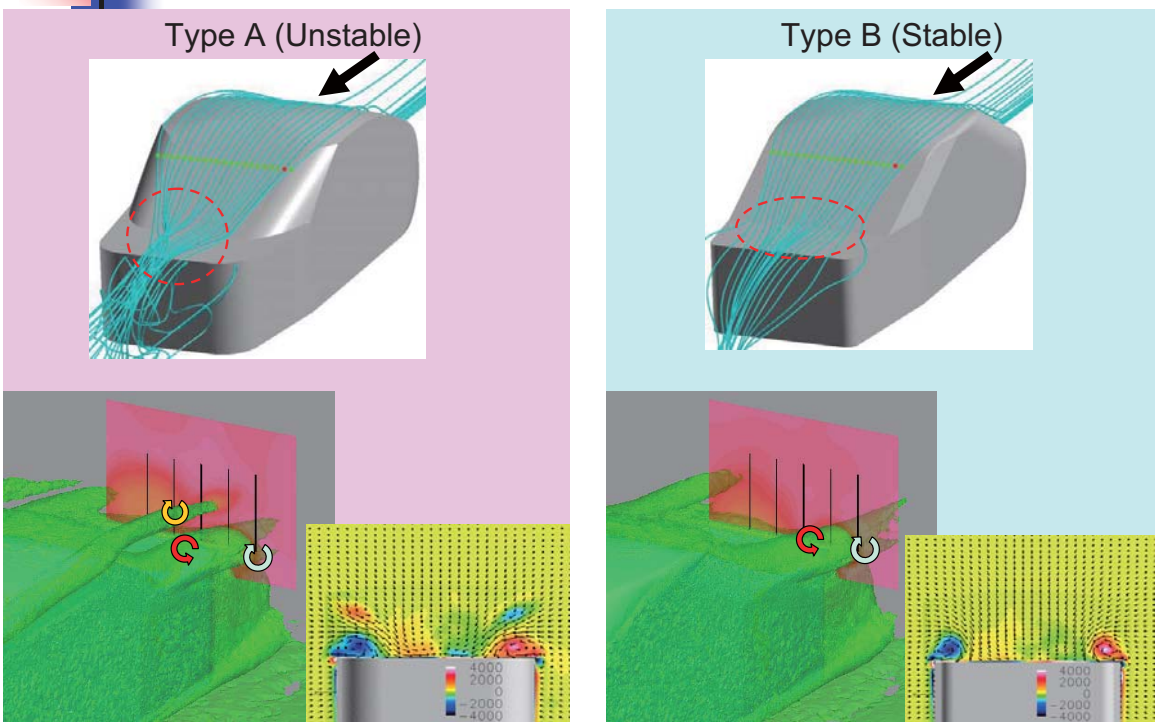
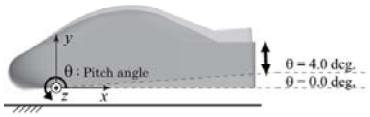
Dynamic Pitch-angle Motion
Flow Structures above the Trunk Deck

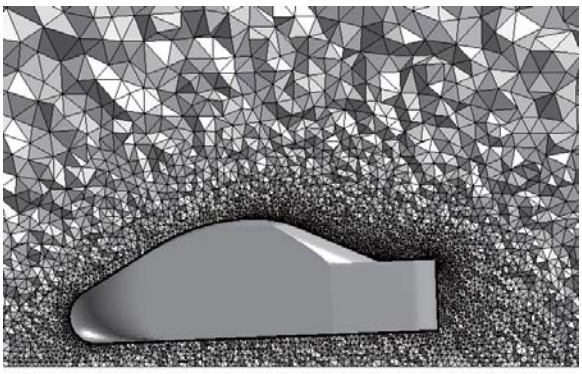


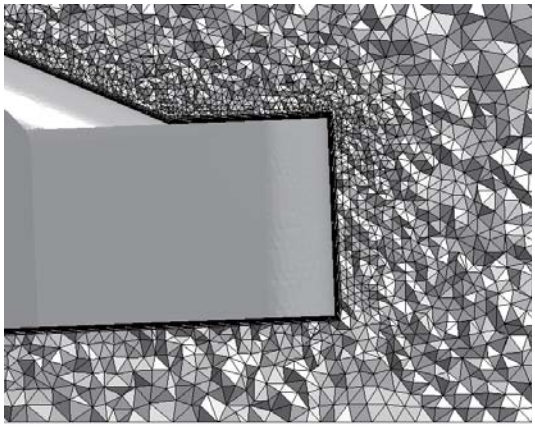
Dynamic Pitch-angle Motion
Forced Oscillation

- ALE Method
- Forced Sinusoidal oscillation: $\theta = \theta_0 + \theta_1 + \sin 2\pi f t$

$$\theta_0 = \theta_1 = 2.0[\mathrm{deg.}], f = 10[\mathrm{Hz}]$$







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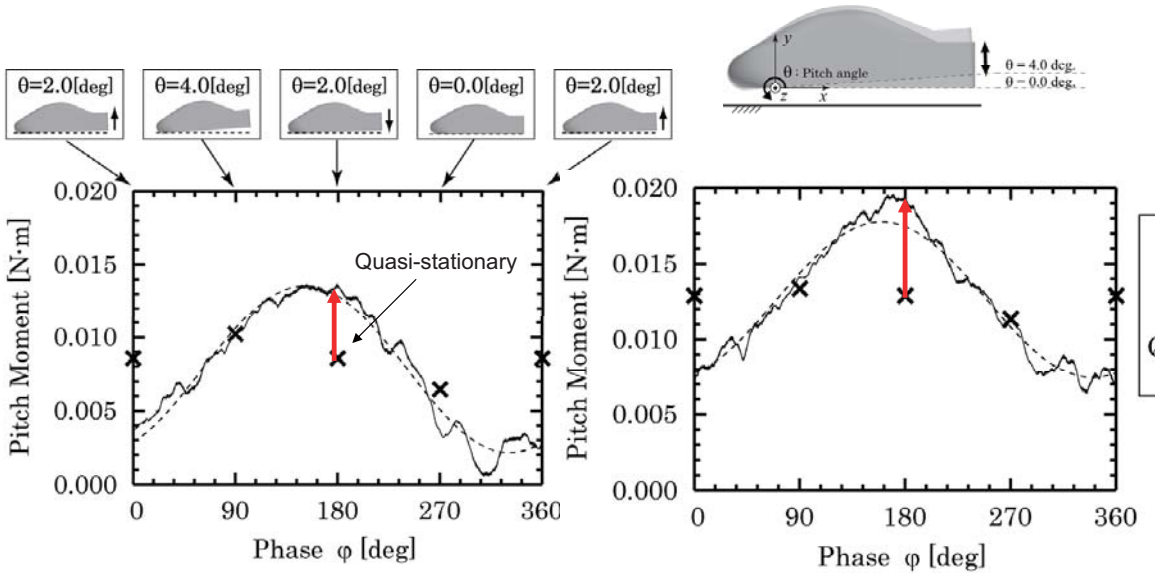
Dynamic Pitch-angle Motion
Transient Pitch Moment



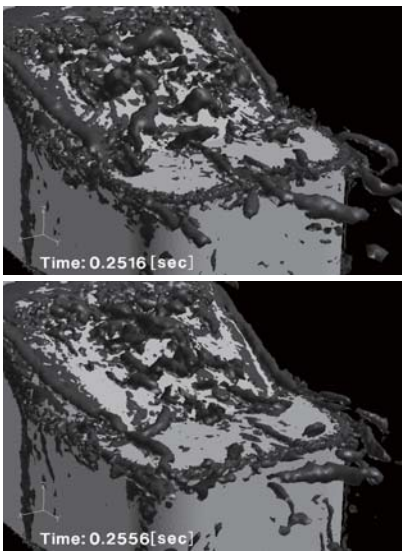
Type A (Unstable)

Type B (Stable)

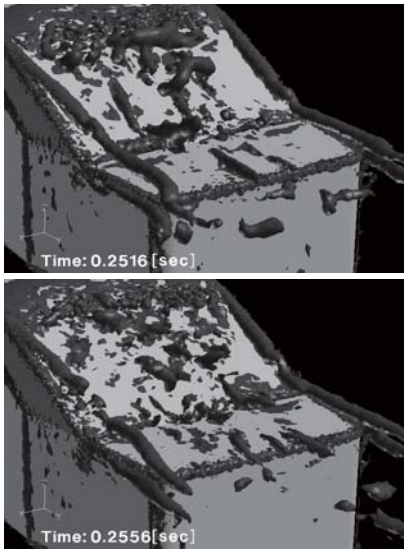
Dynamic Pitch-angle Motion
Vortex Structures above the Trunk Deck

- Type A is more continuous, Type B is more intermittent?

Type A (Unstable)



Type B (Stable)



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Summary and Acknowledgements

- Severe process of road-vehicle development requires an innovative aerodynamic technique.
  - Reduction of drag, establishment of driveability and comfort.
  - Optimization to new power train (fuel cell…).
  - Weight saving enhances the importance of vehicle aerodynamics.
- Establishment of the coupled analysis between aerodynamics and heat/mass, acoustics, vehicle motion is a current issue.
- Unsteady aerodynamics will be a key for the innovation.

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Sequential Data Assimilation: Online Information Fusion Platform for Simulation and Observation Data

Research Organization of Information and Systems

*The Institute of Statistical Mathematics/JST CREST**

Tomoyuki Higuchi

独立行政法人 科学技術振興機構

*Japan Science Technology Agency

Core Research for Evolutional Science and Technology

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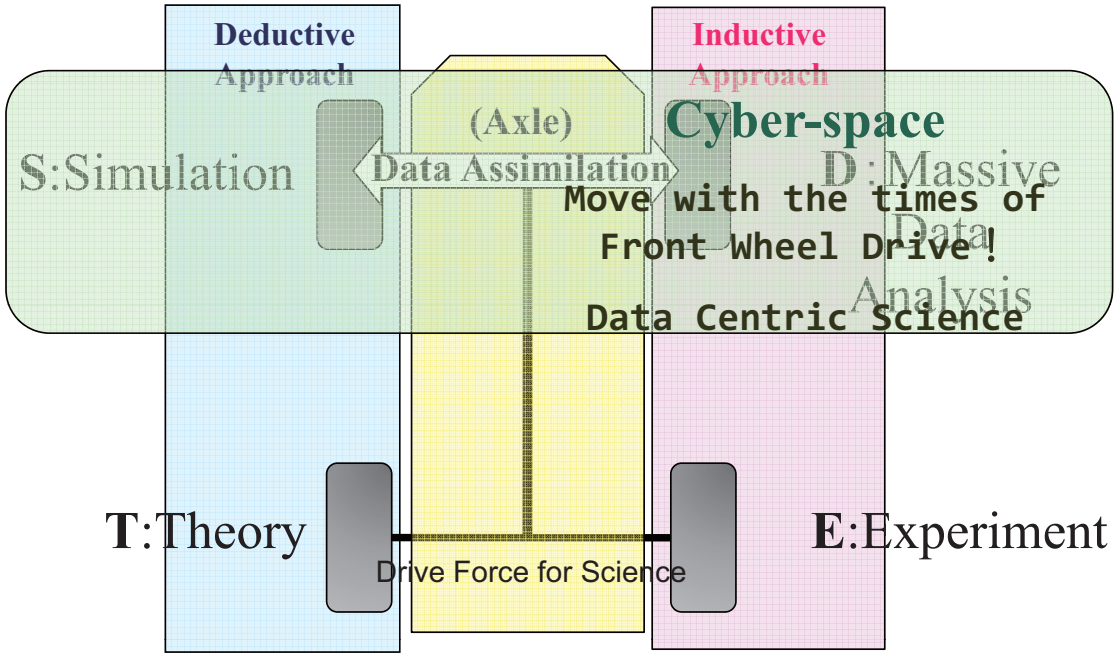
TESD: Four Kind of Methodology of Science



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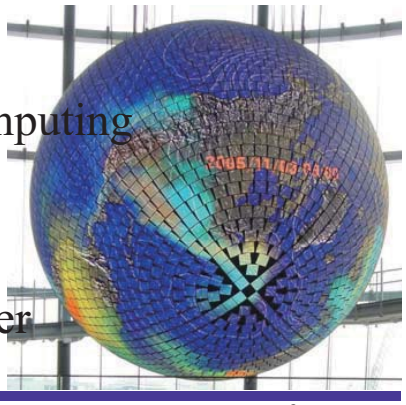
Outline

1. Simulations with uncertainties
2. Data Assimilation (DA)
3. Modeling uncertainties
4. Sequential DA and generalized state space model
5. Ensemble-based nonlinear filtering methods
   1. Ensemble Kalman filter
   2. Particle filter
6. Applications with peta-scale computing
   1. Tsunami Simulation model
   2. Ocean Tide Simulation
   3. Genome Science
7. Next generation of supercomputer
8. Conclusions



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Construction of Simulation Model

（simplified meteorological model around Japan）

PDE to approximate real ph
(continuous time/s

$\frac{\partial x}{\partial t} = cx^2 + \cdots$

PDE : Partial d

Discrete simulation
(discrete time/spac

$x_t = F(x_{t-1})$

(time v
Boun

Nonlinear state spac
(discrete time/space, stoc

$x_t = F(x_{t-1}, v_t)$

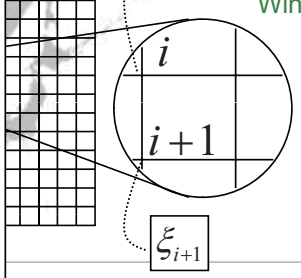
$$x_t = \begin{bmatrix} \xi'_1 \\ \vdots \\ \xi'_i \\ \xi'_{i+1} \\ \vdots \\ \xi'_K \\ \theta \end{bmatrix}$$

variable vector ξ_i is assigned
rid point.

temperature

$\xi_i = (T_i, U_i, V_i)$

Wind vector



n points and observed
e limited.

4

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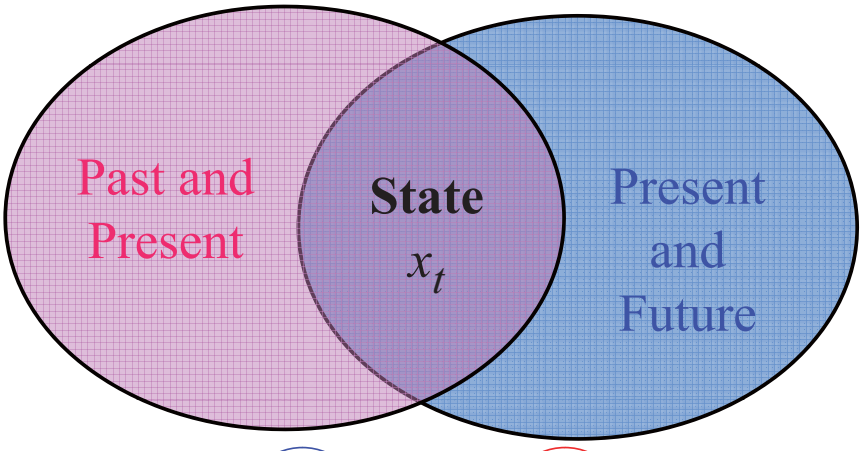
State Vector : Contact point between past and future



State of time t ← $x_t = F(x_{t-1})$ → State of time t-1

Simulation Model

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Simulation

Simulation model

$$x_t = F_t(x_{t-1})$$

time $n \cdot \delta t \to t$

$t = 0,1,2,\ldots,n,\ldots$

δt : simulation time step

x_t: State vector (simulation variables)

x_0 : Initial condition, given

When $x_0 = \alpha$,

$$x_1 = F_1(\alpha)$$
$$x_2 = F_2(x_1)$$
$$\vdots$$
$$x_T = F_T(x_{T-1})$$

Sequence $(x_1, x_2, \cdots x_T)$ is obtained deterministically.

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Simulation including uncertainty

Simulation model

$$x_t = F_t(x_{t-1})$$

x_0 : Initial condition

When $x_0 = \alpha$,

$$x_1 = F_1(\alpha),$$
$$x_2 = F_2(x_1),$$
$$\vdots$$
$$x_T = F_T(x_{T-1})$$

with uncertain evolution

$$x_t \approx F_t(x_{t-1})$$ BC, parameters, …

with uncertain IC

When $x_0 \approx \alpha$,

$$x_1 \approx F_1(\alpha),$$
$$x_2 \approx F_2(x_1),$$
$$\vdots$$
$$x_T \approx F_t(x_{T-1})$$

Sequence $(x_1, x_2, \cdots x_T)$ should be evaluated probablistically.

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What is Data Assimilation ?

- Emerging subject in meteorology and oceanography.
- Methodology to synthesize numerical simulation model and observed data
  - Simulation model can not represent real phenomena accurately.
    - (e.g.) Accurate weather forecast needs good initial conditions.
    - Uncertainty in the model (boundary condition, initial condition, unknown parameters, unknown dynamics...) exists.
  - Observation data have some physical/budgetary restrictions.

Correct variables in numerical simulation model using observation data.

= Data Assimilation

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Objects of Data Assimilation from a viewpoint of Meteorology and Oceanography

[1] To produce the best (better) **initial condition** for forecasting. It is actually realized in the real weather forecast (ex., Japan Meteorological Agency).

[2] To find the best (better) **boundary condition** in constructing a simulation model. This procedure includes a setting of appropriate boundary conditions necessary for dealing with a coupled phenomena.

[3] To attain an optimal **parameter** vector that appears in an empirical law (scheme) employed for describing complicated phenomena which possesses the different time and spatial scales. A **validation** of the empirically given values is regarded as this problem.

[4] To inter/extrapolate (estimate) an physical quantity at times and locations without observations based on a numerical simulation model. This procedure is called "a **generation of re-analysis dataset** (product)". This dataset is used to discover a new scientific findings by general geophysical researchers.

[5] To conduct an experiment with a virtual observation network and perform a **sensitivity analysis** in an attempt to construct an effective observation network system with less budgetary cost and less consuming time.

(ex. Kamachi et al., 2006)

Modeling uncertainties

•Represent a wide variety of uncertainty in a research target by distribution function.

•Understand a complex targets, NOT from its simple statistics such as mean, BUT from its distribution directly.

Notion of Probability: The machinery of probability theory is used to describe the uncertainty in model parameters or choice of model itself.

Probability theory provides a framework for quantification and manipulation of uncertainty. We will introduce a basic concept of probability theory next.

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Bayesian View
Central Role in Pattern Recognition and Machine Learning

It expresses how probable the observed dataset is for different settings of the parameter vector X.

Data dist.（likelihood function） Prior dist.

Posteiror dist.

$$p(x \mid y) \equiv \frac{p(y \mid x) \cdot p(x)}{p(y)} \propto p(y \mid x) \cdot p(x) = p(x, y)$$

Bayes' Theorem

It is independent of data Y, and describes a conviction degree against X numerically.

X: Parameter vector

Y: Data

Probability of data (Since data is given (the actually observed one), it takes some value.)

Joint dist.

We are interested in estimating a posterior distribution in most of circumstances.

We would like to be able to quantify our expression of uncertainty and make a precise revisions of uncertainty in the light of new evidence, as well as subsequently to be able to take optimal actions/decisions as a consequence.

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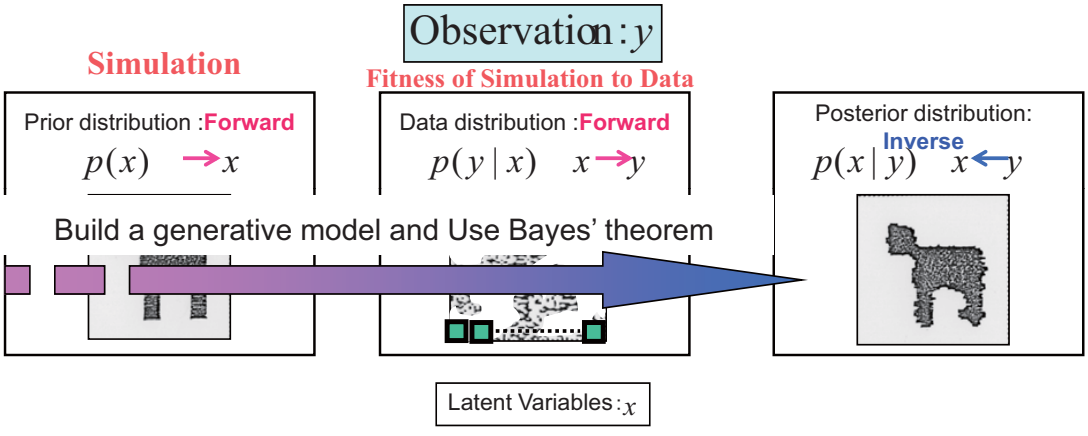
Generative Model, Inversion with Bayes' theorem, and Data Assimilation



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Data Assimilation in Generalized State Space Model

State Vector (Simulation variables)

$L \Rightarrow L$: nonlinear map

Δt : sampling time of observations

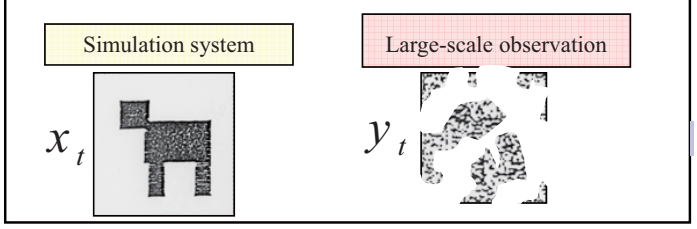
δt : simulation time step

$\Delta t = 1 >> \delta t$

$$x_t = F(x_{t-1}, v_t)$$ **Stochastic simulation model**

$$y_t = Hx_t + w_t$$ Observation model (Measurement model)

Bayesian Approach



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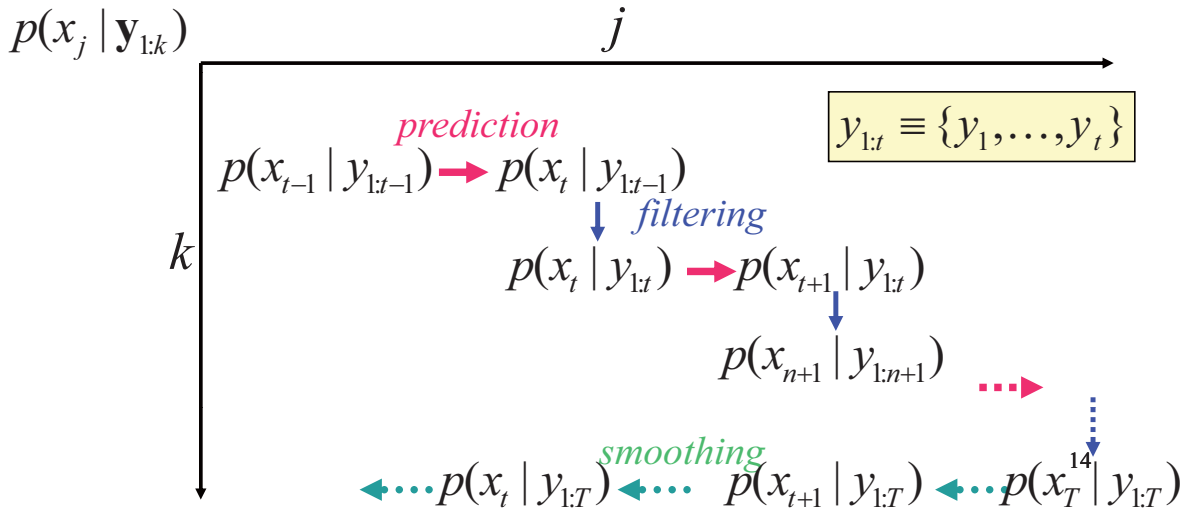
Conditional Distribution Recursive formula

predictive density: $p(x_t \mid \mathbf{y}_{1:t-1})$ Today's economic situation given yesterday's stock market data

filter density: $p(x_t \mid \mathbf{y}_{1:t})$ Today's economic situation estimated by the stock market data up to today

smoother density: $p(x_t \mid \mathbf{y}_{1:T})$ Today's economic situation analyzed by using all available data when we look back on the today in future



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Prediction

$$p(x_t \mid y_{1:t-1})$$

$$= \int p(x_t, x_{t-1} \mid y_{1:t-1}) dx_{t-1}$$

$$= \int p(x_t \mid x_{t-1}, y_{1:t-1}) p(x_{t-1} \mid y_{1:t-1}) dx_{t-1}$$

$p(x_t \mid x_{t-1}, y_{1:t-1}) = p(x_t \mid x_{t-1})$ Markov property（1）

$$= \int p(x_t \mid x_{t-1}) p(x_{t-1} \mid y_{1:t-1}) dx_{t-1}$$

Filter pdf at time *t-1*

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filtering

$$p(x_t \mid y_{1:t})$$

Posterior, Belief

$$= p(x_t \mid y_t, y_{1:t-1})$$

$$= \frac{p(x_t, y_t \mid y_{1:t-1})}{p(y_t \mid y_{1:t-1})}$$

$$= \frac{p(y_t \mid x_t, y_{1:t-1}) \cdot p(x_t \mid y_{1:t-1})}{p(y_t \mid y_{1:t-1})}$$

Markov Property（2）

$p(y_t \mid x_t, y_{1:t-1}) = p(y_t \mid x_t)$

$$= \frac{p(y_t \mid x_t) \cdot p(x_t \mid y_{1:t-1})}{p(y_t \mid y_{1:t-1})}$$

$$= \frac{p(y_t \mid x_t) \cdot p(x_t \mid y_{1:t-1})}{\int p(y_t \mid x_t) \cdot p(x_t \mid y_{1:t-1}) dx_t}$$

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Smoothing

$$p(x_t \mid y_{1:T})$$

$$= \int p(x_t, x_{t+1} \mid y_{1:T})dx_{t+1}$$

$$= \int p(x_t \mid x_{t+1}, y_{1:T}) \cdot p(x_{t+1} \mid y_{1:T})dx_{t+1}$$

$$= \int p(x_t \mid x_{t+1}, y_{1:t}) \cdot p(x_{t+1} \mid y_{1:T})dx_{t+1}$$

$$= \int \frac{p(x_t, x_{t+1} \mid y_{1:t})}{p(x_{t+1} \mid y_{1:t})} \cdot p(x_{t+1} \mid y_{1:T})dx_{t+1}$$

$$= \int \frac{p(x_t \mid y_{1:t}) \cdot p(x_{t+1} \mid x_t, y_{1:t})}{p(x_{t+1} \mid y_{1:t})} \cdot p(x_{t+1} \mid y_{1:T})dx_{t+1}$$

$$= p(x_t \mid y_{1:t}) \cdot \int \frac{p(x_{t+1} \mid x_t)}{p(x_{t+1} \mid y_{1:t})} \cdot p(x_{t+1} \mid y_{1:T})dx_{t+1}$$

Filter Dist. Smoothing Dist. Prediction Dist.

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Sequential Data Assimilation

Estimate PDF of state vector x_t or its moments (mean, variance, …) sequentially on each observation

y_{t-1}

$p(x_{t-1} \mid y_{1:t-1})$

$\left(p(x_i \mid y_{1:k}) = p(x_i \mid y_1, y_2, \cdots, y_k) \right)$

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Challenging problem: Huge dimension and inversion

- Data Assimilation = Estimation problem of state vector x_t:

(system model) $x_t = F_t(x_{t-1}, v_t | x_0)$

(observation model) $y_t = H_t x_t + w_t$ or $y_t = h_t(x_t) + w_t$

  - x_t : All variables in simulation model
  - y_t : All observed variables
  - v_t : Stochastic part to represent uncertainty of model (boundary condition, …)
  - w_t : Observation error
  - v_t, w_t : Normally Gaussian x_0: Initial condition

dimension x_t :10^4~10^6 y_t :10^2~10^5 $\dim(x_t) >> \dim(y_t)$

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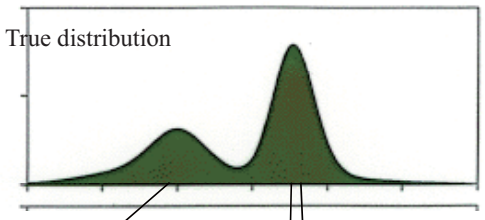
Numerical representation of distribution

$p(x_t \mid y_{1:t-1}), p(x_t \mid y_{1:t}), p(x_t \mid y_{1:T})$



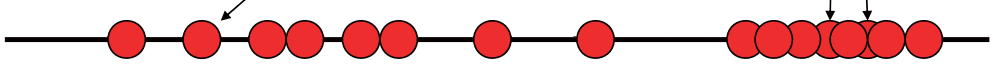
Monte Carlo approximation

Represent pdf by the actual realizations.

N: # of particles

$$p(x_t \mid y_{1:t-1}) \cong X_{t|t-1} \equiv \left[x_{t|t-1}^{(1)}, x_{t|t-1}^{(2)}, \ldots, x_{t|t-1}^{(N)}\right]$$

$$p(x_t \mid y_{1:t}) \cong X_{t|t} \equiv \left[x_{t|t}^{(1)}, x_{t|t}^{(2)}, \ldots, x_{t|t}^{(N)}\right]$$



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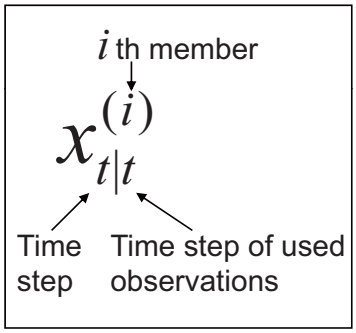
Sequential DA Methodology

- Ensemble Kalman Filter (EnKF) is widely used.
  - Conditional PDF is approximated by a set (ensemble) of realizations.
  - Kalman Filter is used for filtering.
- Application of Particle Filter (PF) is rare.
  - This is also ensemble based.

$$p(x_t \mid y_{1:t-1}) \cong \frac{1}{N}\sum_{i=1}^{N}\delta(x_t - x_{t|t-1}^{(i)}) \qquad \left\{x_{t|t-1}^{(i)}\right\}_{i=1}^{N}$$

$$p(x_t \mid y_{1:t}) \cong \frac{1}{N}\sum_{i=1}^{N}\delta(x_t - x_{t|t}^{(i)}) \qquad \left\{x_{t|t}^{(i)}\right\}_{i=1}^{N}$$



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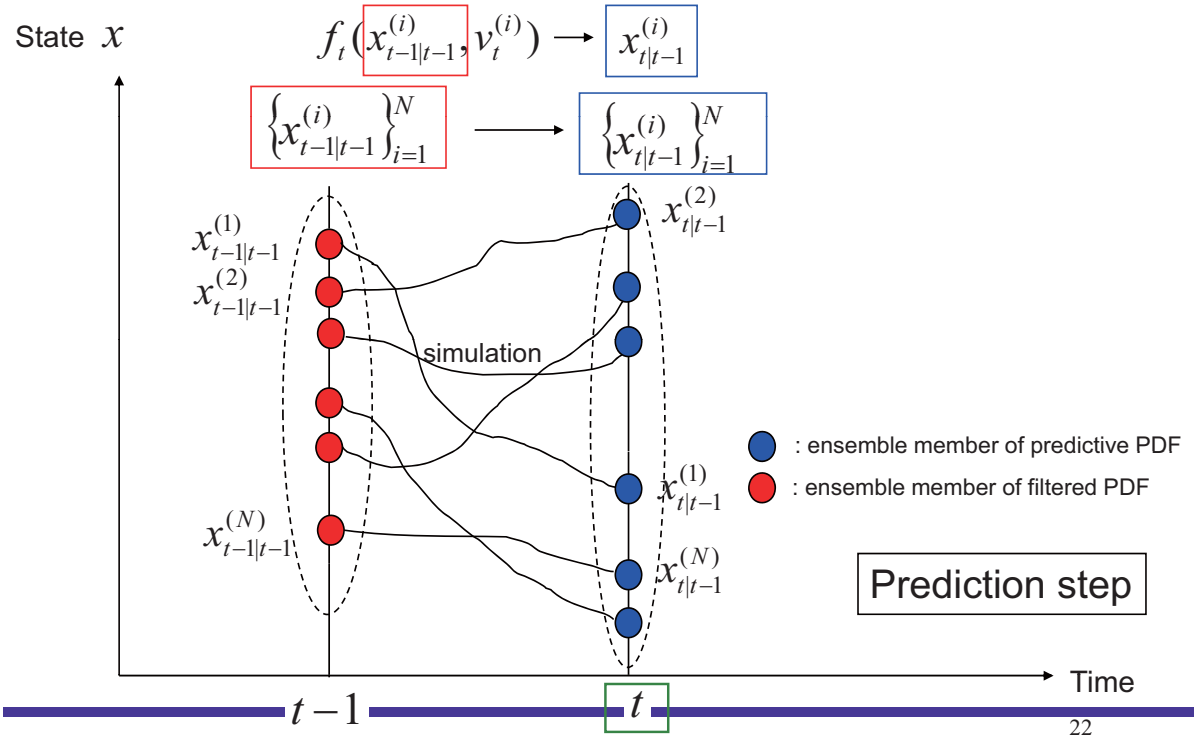
ISM

Prediction Step (Common in EnKF and PF)



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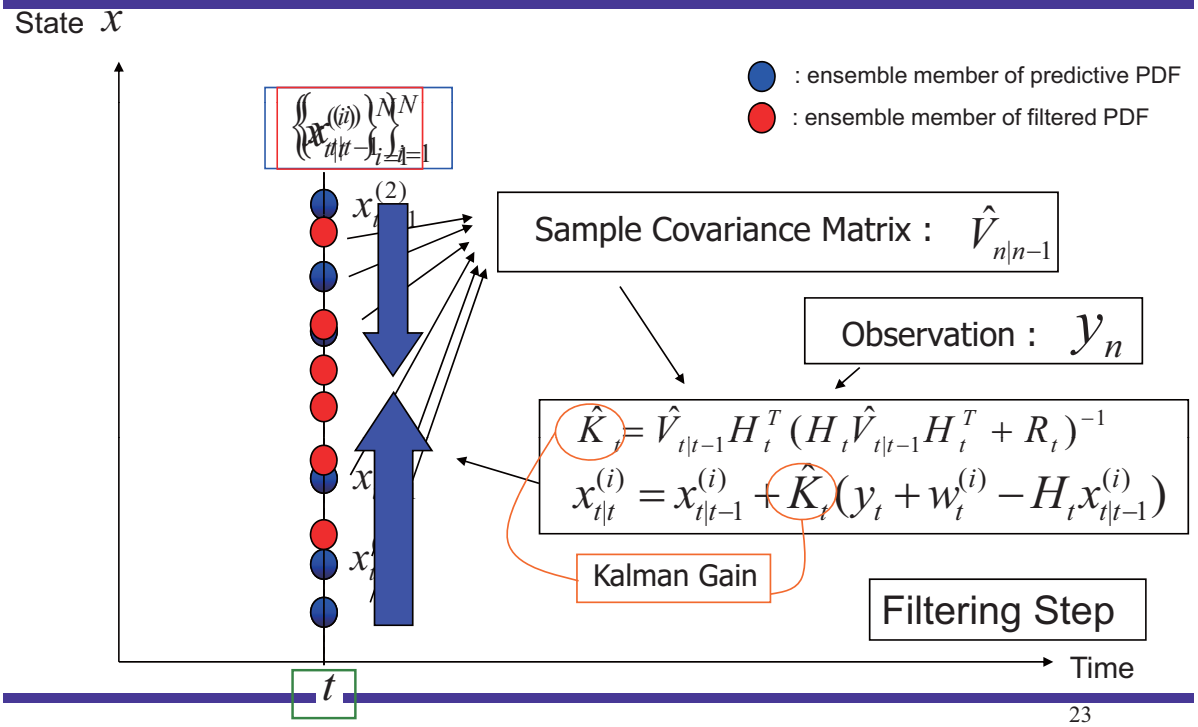
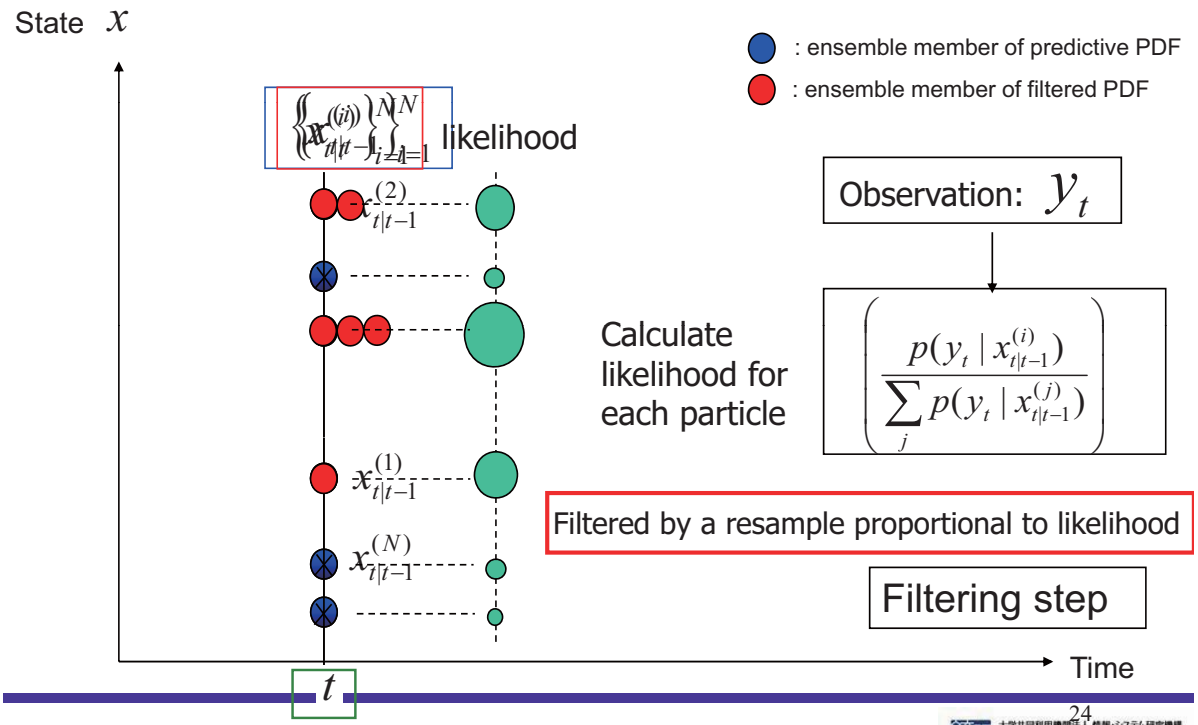
Filtering step of EnKF



ISM

Filtering Step of PF



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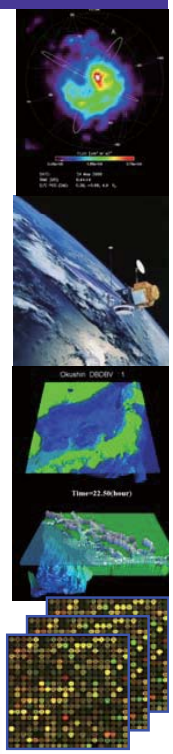
Projects in progress

- Coupled Ocean-Atmosphere model
  Genta **Ueno** (ISM/JST CREST)
  T. Kagimoto (JAMSTEC, FRCGC), N. Hirose (Kyushu Univ., RIAM)
- Tsunami model
  Kazuyuki **Nakamura** (JST CREST)
  N. Hirose (Kyushu Univ., RIAM)
- Ocean tide
  Daisuke **Inazu** (JST CREST)
  T. Sato, S. Miura (Tohoku Univ.), and others (Alaska Univ.)
- 3D structure of ring current
  Shin'ya **Nakano** (JST CREST),
  Y. Ebihara (Nagoya Univ.) , M.-C Fok (NASA)
  S.-I. Ohtani, P.C.Brandt（Johns Hopkins Univ.)
- Genome informatics
  Ryo **Yoshida** (ISM/JST CREST)
  Miyano lab. (Tokyo Univ./IMS)



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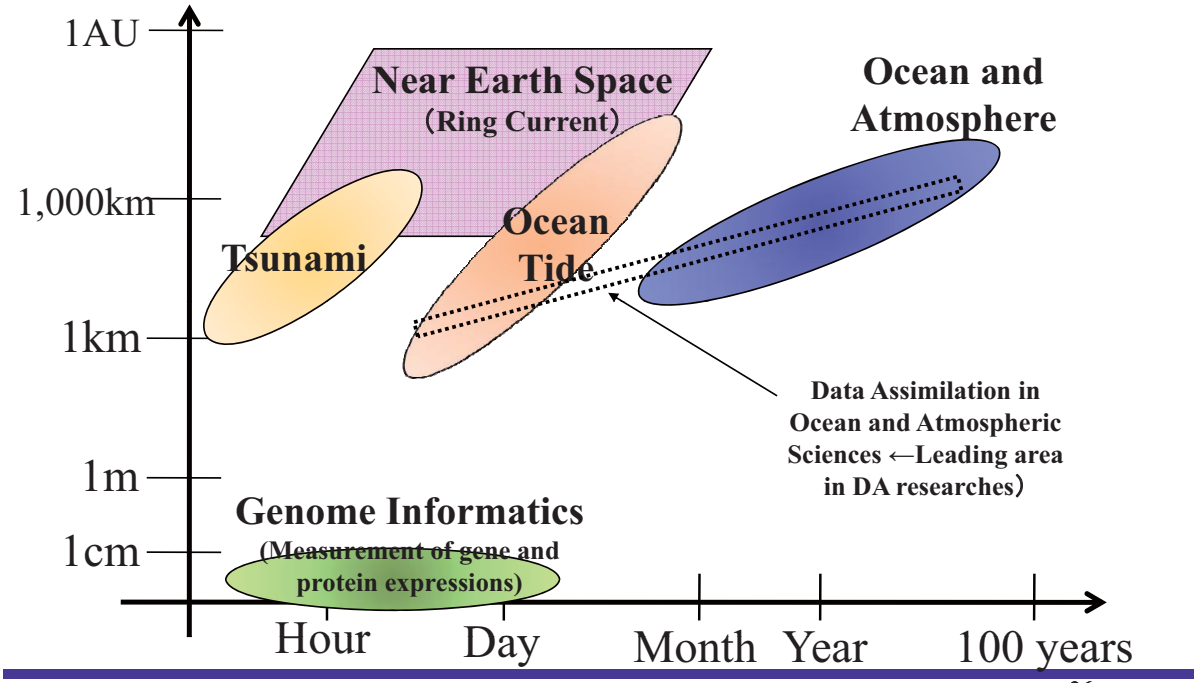
Time and Spatial Scale



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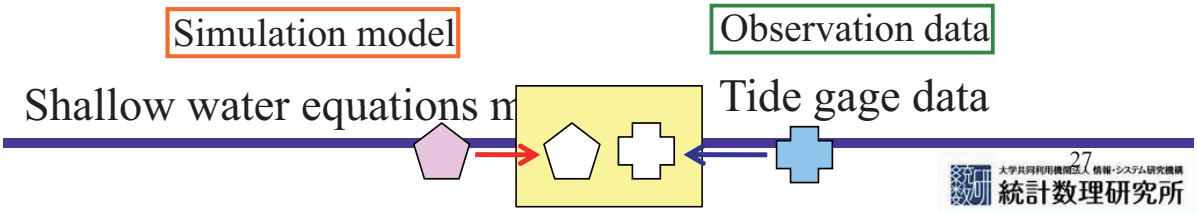
Revisit : What is Data Assimilation?

- Emerging subject in meteorology and oceanography.
- Methodology to synthesize numerical simulation model and observed data
  - Simulation model can not reflect real physics accurately.
    - (e.g.) Accurate weather forecast needs good initial conditions.
    - Uncertainty in the model (boundary condition, initial condition, unknown parameters, unknown dynamics...) exists.
  - Observation data have some physical/budgetary restrictions.

Correct variables in numerical simulation model using observation data. = Data Assimilation



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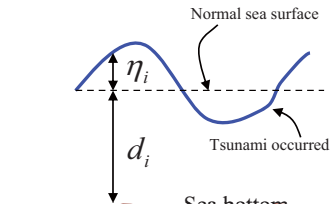
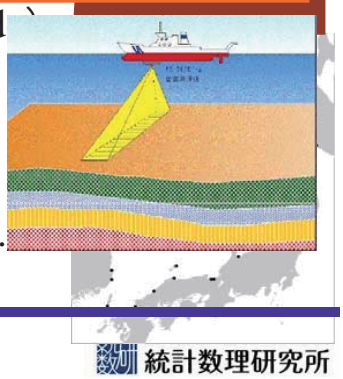
Tsunami Simulation Model

- Based on PDE→Shallow water equations [Choi *et al.* 01]
- Discretized temporally and spatially.
  - 4 physical variables at each grid i .
    - Flow vector (longitudinal/latitudinal) : (U_i, V_i)
    - Displacement of sea surface height : η_i
    - Water depth at each grid : d_i ← Uncertainty in measured water depth!
  - # of grid points: 192 (longitude) × 240 (latitud
    - Half of them are on the sea.
    - Dimension of state vector is about 9×10^4.
- Propagation speed depends on water depth.
  - Deep water makes tsunami propagation faster.





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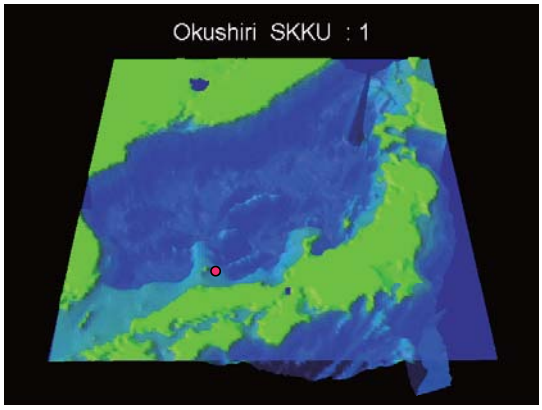
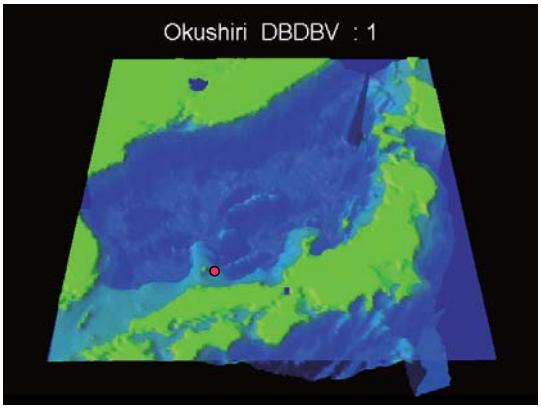
Numerical Simulation (Not DA)

- Simulation of Okushiri Tsunami
  - Simulation based on topographies made by different organizations.
  - It looks similar, but time series of sea surface displacement at a point (●) is ...

(From Japan Coast Guard)





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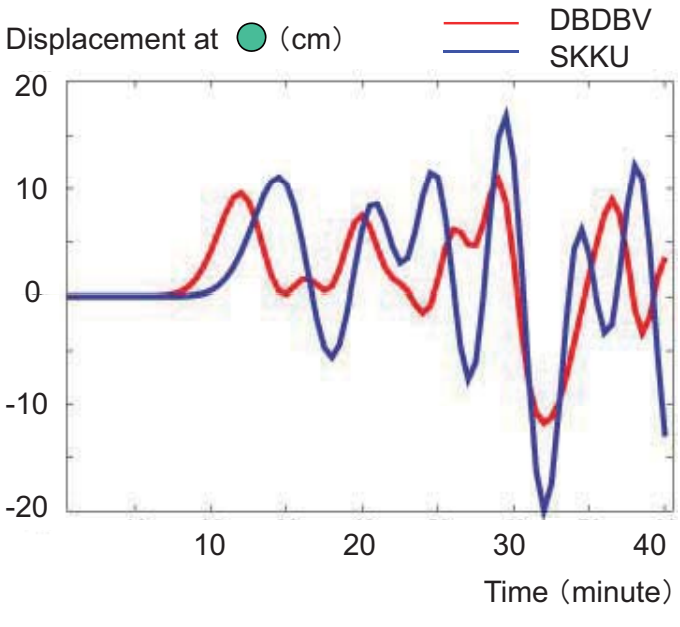
Comparison of Sea Surface Displacement



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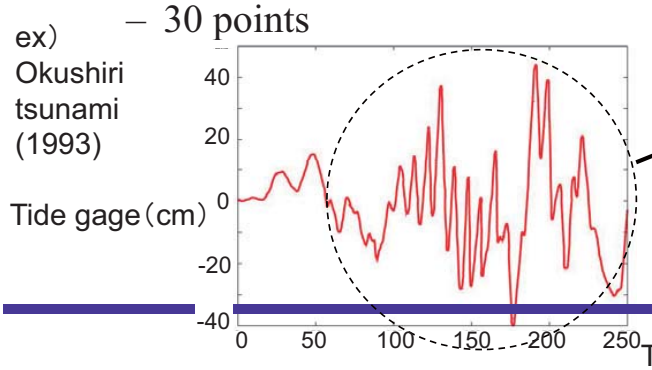
Observation Data

- Tide gage data:
  - (Linear/Nonlinear) Response to sea surface displacement at instrument installation site.
  - One dimensional time series.
- Number of tide gage stations:
  - 30 points



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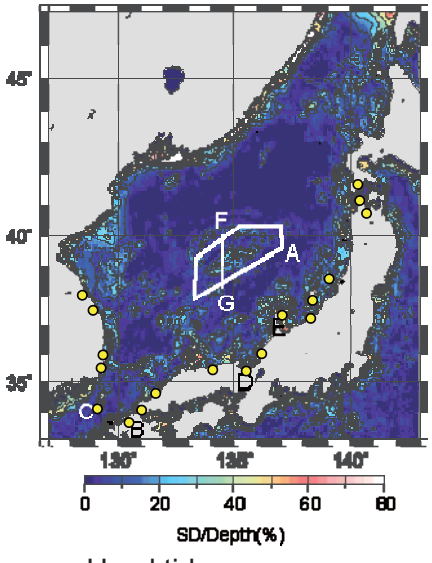
Application to Real Data

- Analysis by real tsunami occurred in the Japan Sea in 1993.

•The depths in and around Yamato Rises (area A) varies among 4 bottom topography data set.

•Uncertainty is introduced into South Rises and around area as linear combination of 4 data sets.



j : number of data sets

$$d_m^{(i)} = \sum_j w_j^{(i)} d_{m,j} \quad , \quad w_j^{(i)} \sim N(0.25, \sigma^2)$$

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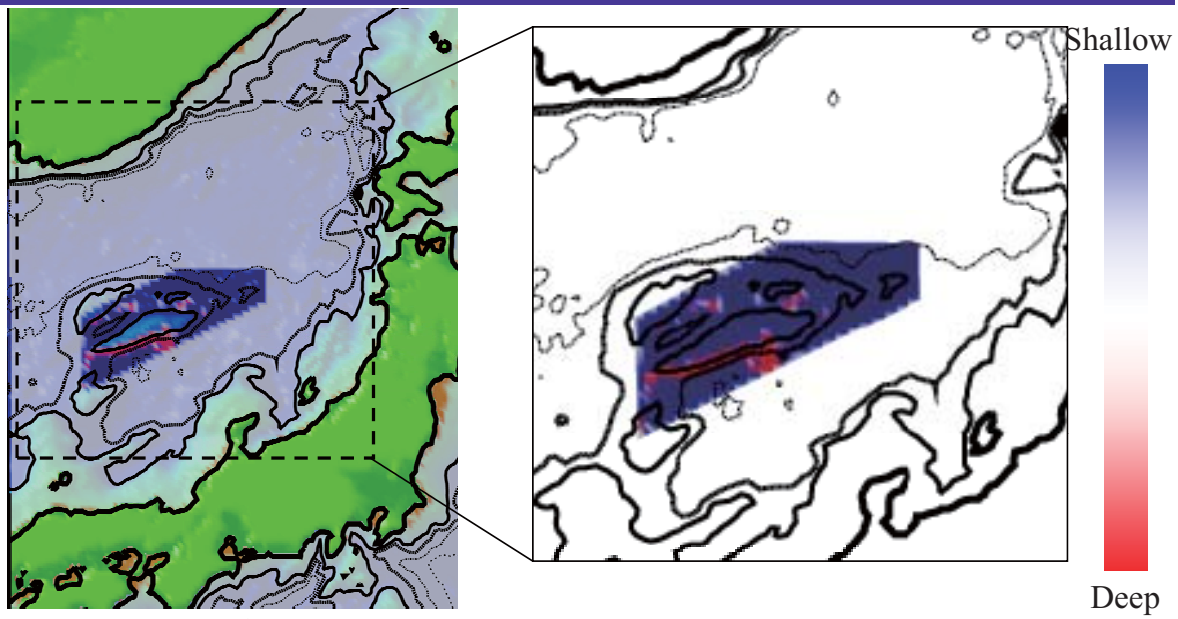
DA result



•South Rise might be shallower than public data.
•Deeper area exists in south slope.

Personalized Simulation :

A boundary condition is assimilated to local information.

We introduce a local/personal information into a numerical simulation model and personalize the simulation for each location/person.

Motion Eq. : $\mathbf{v}$

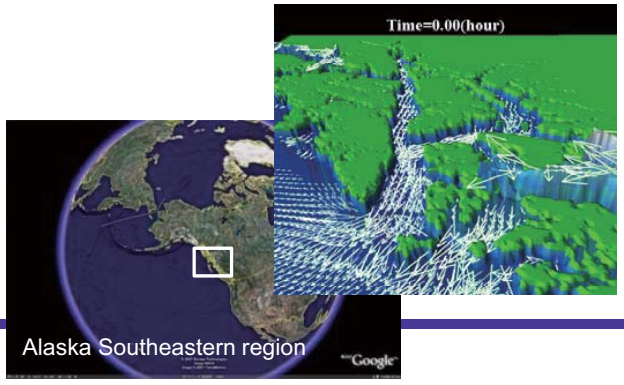
$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\cdot\nabla)\mathbf{v} + \mathbf{f}\times\mathbf{v} = -g\nabla\eta - \gamma_b \frac{\mathbf{v}|\mathbf{v}|}{H} + A_H\nabla^2\mathbf{v}$$

Sea Bottom friction coefficient

Sea depth

Continuous Eq. :

$$\frac{\partial \eta}{\partial t} + \nabla\cdot(\mathbf{v}H) = 0$$



$\mathbf{v}$: 2-dimensional flow vector
η : Water surface height
H : Water depth, $\mathbf{f}$: Coriolis parameter

Ocean tide simulation by our CREST project

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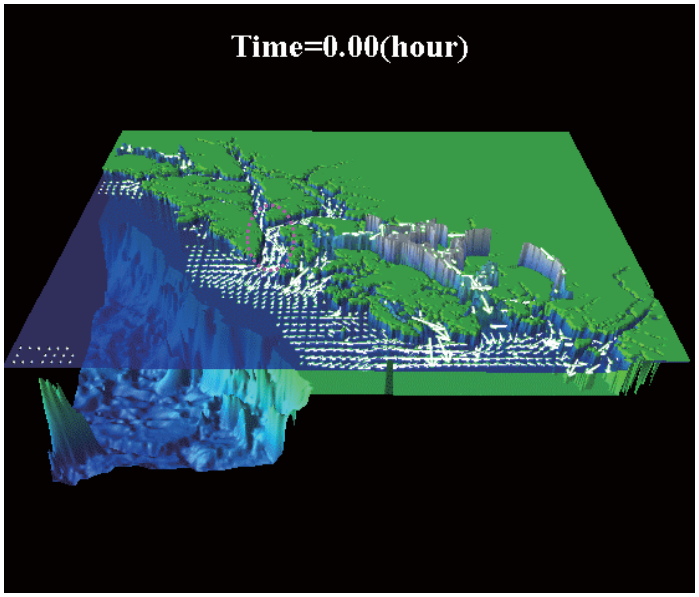
Water level and Flow vectors



Sea level range is About ±5 m. Current speed is (much) more than 1 m/s at the mouth of Chatham Strait.

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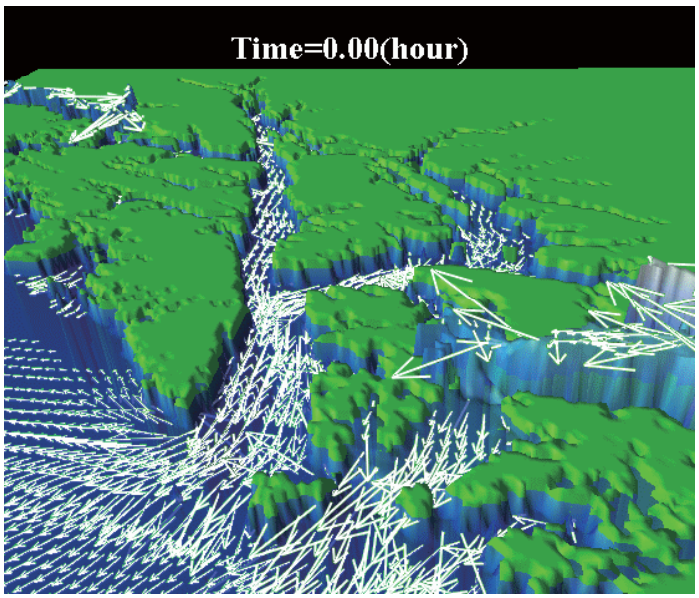
Water level and flow vectors（Closeup）



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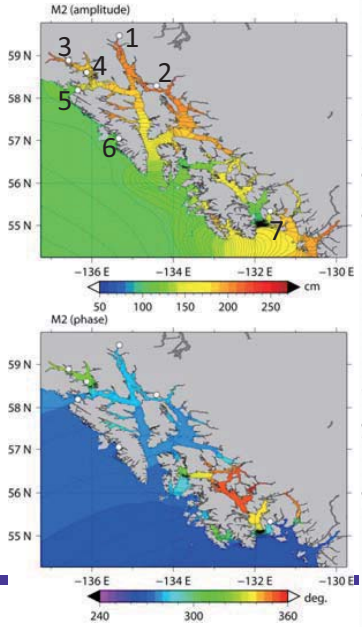
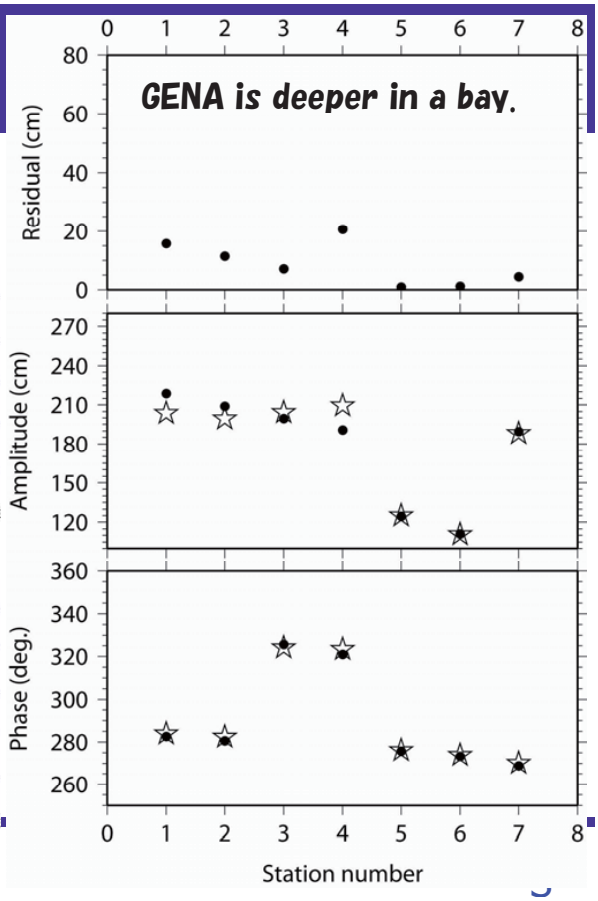
M_2component tide
Result with GINA

GENA shows a great performance in representing an ocean tide.

Amplitude

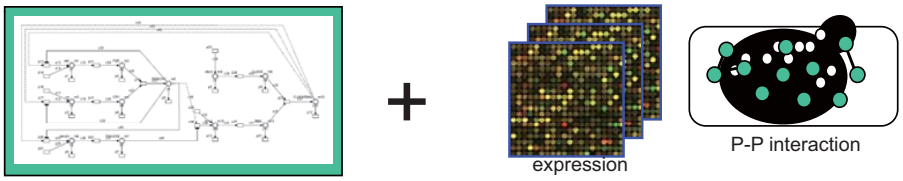
Phase





Genomic Data Assimilation

Statistical framework to link simulation model and data



Simulation model　　Biological data

Formulated by the generalized State Space Model

$$x_t = f(x_{t-1}, v_t, \theta)$$ System model

$$y_t = Hx_t + w_t$$ Observation model

x_t : state vector at time t,　f : simulation devise,　$t = 1, \ldots, T$

v_t : system noise,　θ : parameter vector,

y_t : observation vector at time t,　H : observation matrix,

$w_t \sim N(0, \sigma^2)$: observation noise

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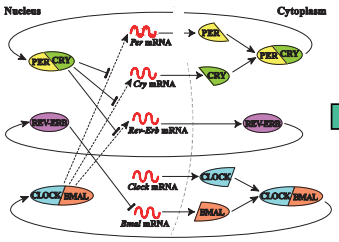
Circadian Rhythm Model with HFPN

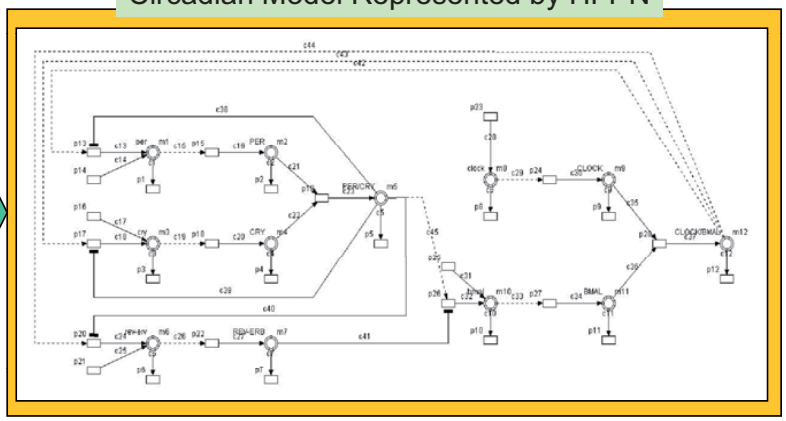
HFPN (Hybrid Functional Petri Net) : A graphical programming language suitable to model biological pathways and can be used for simulations

Circadian Rhythm Model of Mouse



Fujii et al. 2005

Circadian Model Represented by HFPN



45 parameters (12 states),

4 observations

Parameters

$m_1(0),\ldots,m_{12}(0)$	:Initial values
k_1,k_2,k_3,k_4	:Speeds
s_1,s_2,s_3,s_4	:Thresholds
τ^2,σ^2	:Noise variances

時不変パラメータ(速度定数(14)と敷居値(7)及び初期値(12))数33, 状態が12

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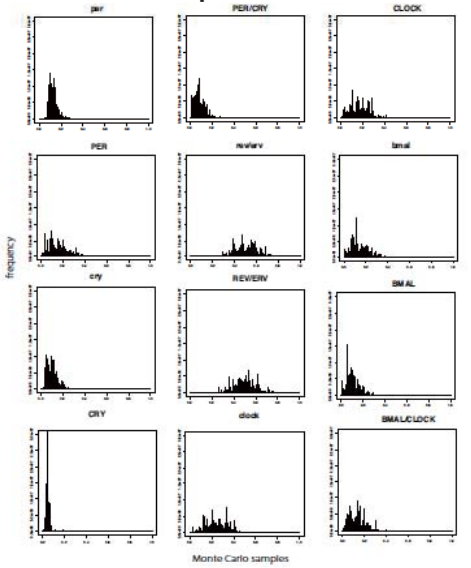
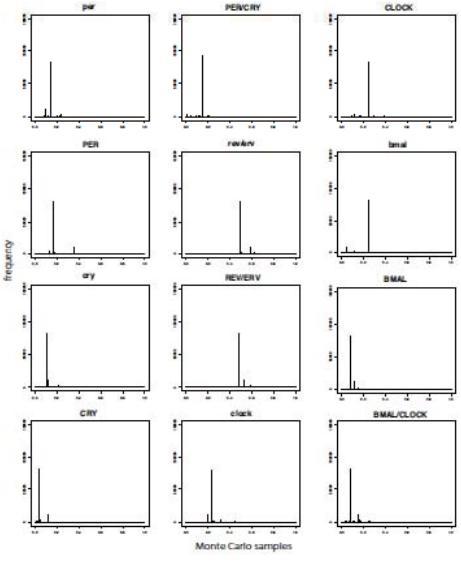
Toward Peta-scale Computing

100,000,000 particles（1億）



100,000 particles:10万



大学共同利用機関法人 情報・システム研究機構 統計数理研究所

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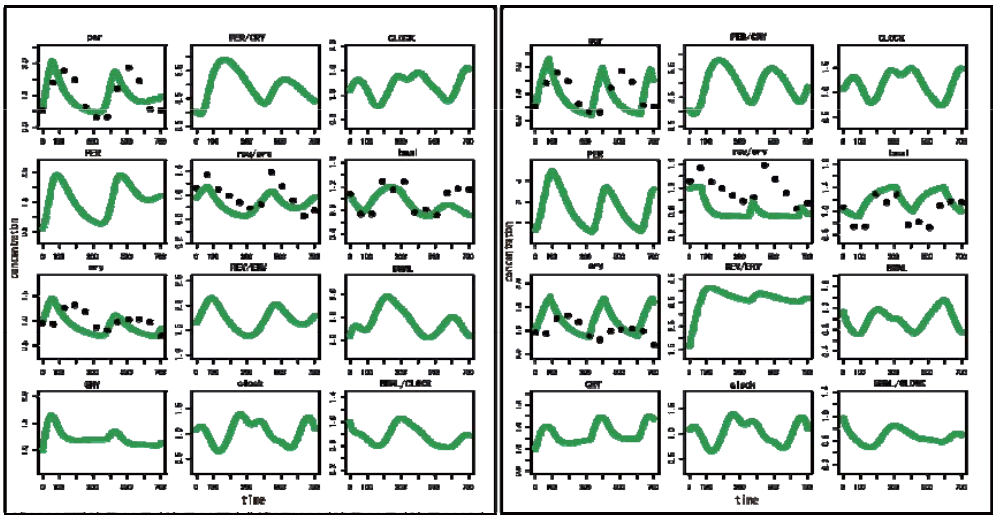
Prediction

100,000,000 particles（1億）　100,000 particles:10万



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Next-Generation of Supercomputer in Japan at Kobe

Japanese Government will spend more than 1 billion US$ for this national project.

■Grand Challenge:
-- Nanotech (Institute for Molecular Science)
-- Life Science (RIKEN)

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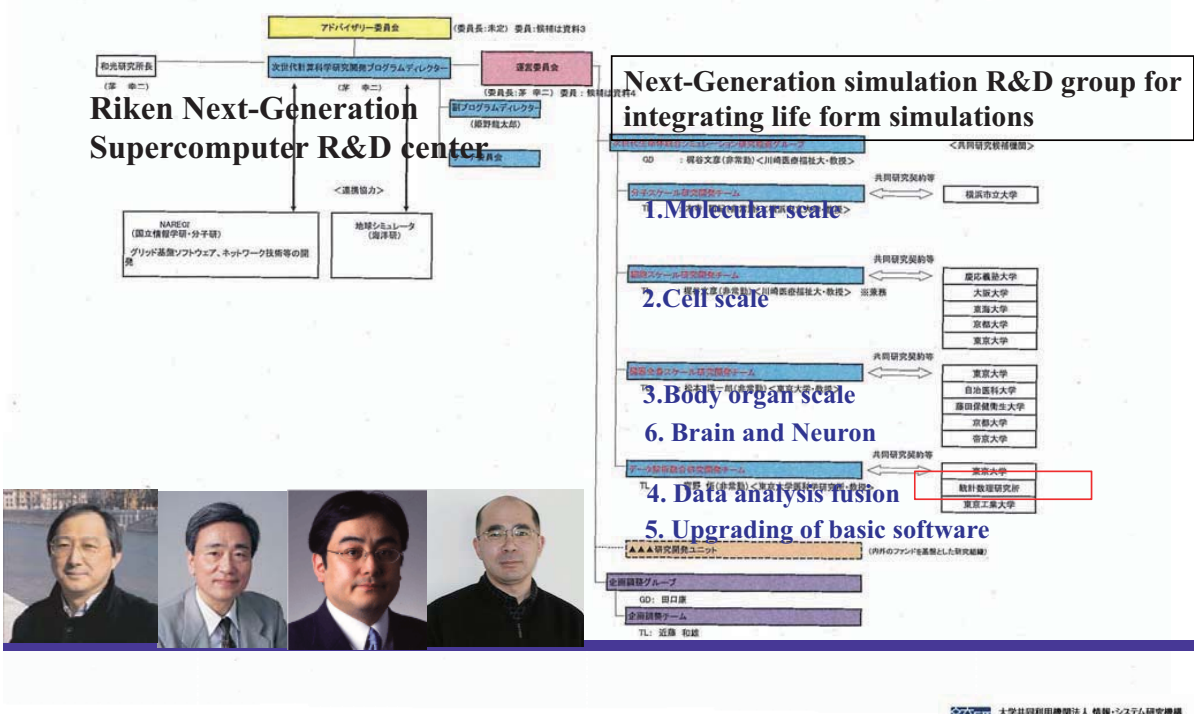
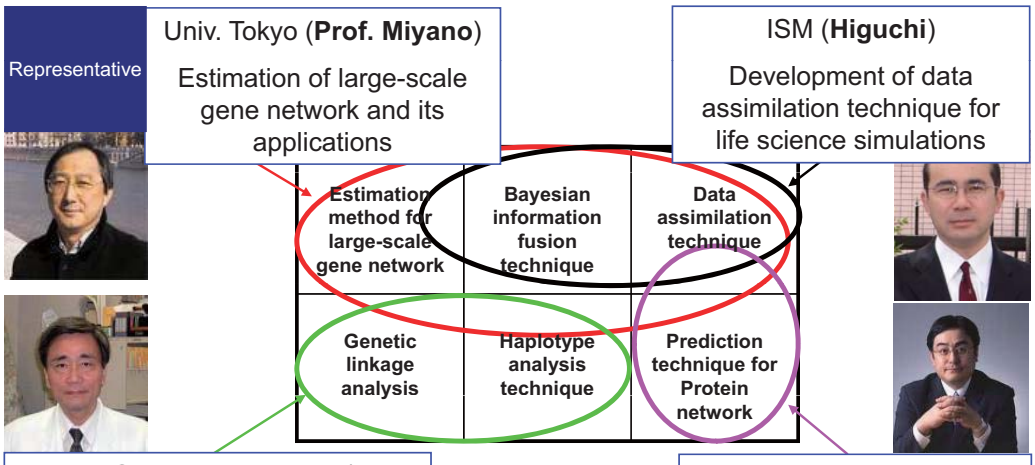
Development for next-generation simulation software for whole human body



統計数理研究所

Data analysis fusion Team



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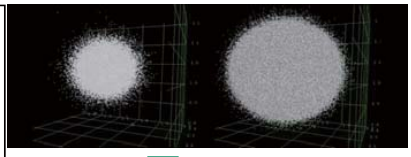
Attempt to realize personalization technique

Making a parallel computation scale larger enables us to carry out a data-dependent simulation, and results in drawing a scenario and in making a risk assessment.

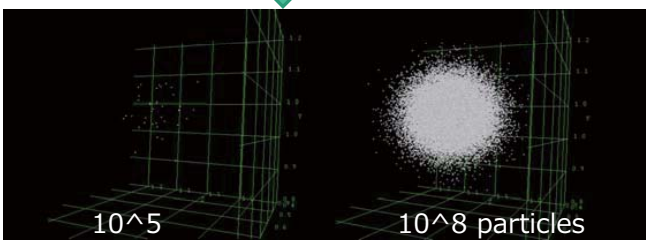
Prior and posterior distributions for three parameters among parameters estimated PF are demonstrated in 3-dimensional space.



Prior distribution of parameters
（left：10^5 right: 10^8）

Estimation by PF

Although the PF with 10^5 particles results in the PDF with a small number of particles, the PF with 10^8 particles leaves many particles.



Posterior distribution of parameters

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Perspective of our Project

"Creation of meta-simulation model"

1. We automate a procedure searching for better simulation model to describe real phenomena.

2. We develop a procedure to generate a new simulation model that has greater ability of predictive performance than existing ones.

3. We give consistent view to assessment of simulation model that is said to be subsidiary problem in simulation science; Maximum Likelihood Principle.

4. We give a platform to design a measurement system in an attempt to enhance a scientific return together with reducing a total budgetary cost.

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EFD/CFD Activities in Research for Reusable Launch Vehicles

再使用型宇宙往還機に向けた研究におけるEFD/CFDの取り組み

Yasuhiro TANI, Shigeru ASO, Kentaro HAYASHI, Kei INOUE,
Kohei YAMAGUCHI and Takuro ISHIDA

谷 泰寛、麻生 茂、林健太郎、井上 慶、山口耕平、石田拓郎

Department of Aeronautics and Astronautics, Kyushu University
Fukuoka, Japan

Second Workshop of Integration of EFD and CFD, 23-24 Feb. 2009

Contents

1. Research Area in our Laboratory
2. Experimental Facilities and CFD Tools
3. Aerodynamic characteristics of RLV configuration
4. Aerodynamic heating reduction research
5. Fuel/Air mixing of SCRAM jet engine combustor

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Research Area in our laboratory

- High and Low Speed Aerodynamic Characteristics of Reusable Launch Vehicle (RLV)
- Reduction of aerodynamic heating during reentry phase for the RLVs
- Future aerospace propulsion system (SCRAM-jet engin, PDE)
- Ecological aircraft for future commuter air transportation

Research activities on RLVs

- **Aerodynamic characteristics**

  fuselage cross sectional configuration

- **Reduction of Aerodynamic heating**

  opposing jet, Film cooling

- **Engines for hypersonic flight**

  scramjet engine, Pulse detonation engine

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Experimental Facilities in use

Test facilities in Department of Aeronautics and Astronautics, Kyushu univ.

- Low Noise Low speed wind tunnel
- Supersonic wind tunnel
- Transonic wind tunnel

Test facilities in Space Transportation Systems Lab.

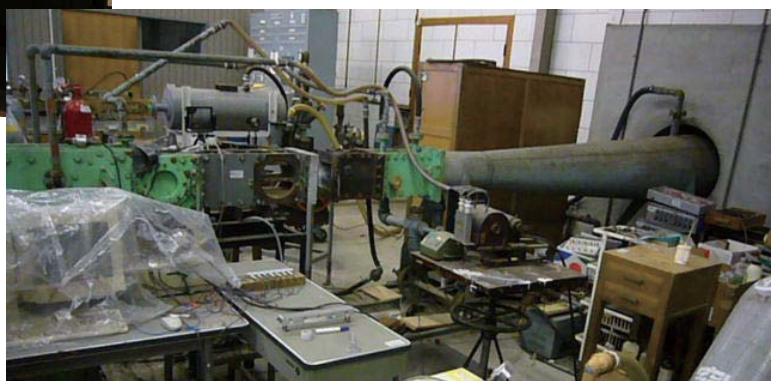
- Detonation driven Expansion tube
- Free piston shock tunnel
- Shock Tube

Other test facilities in use

- ISAS/JAXA Supersonic wind tunnel and Transonic wind tunnel

Former Wind tunnels in Hakozaki Campus

2m Low speed wind tunnel



15cm Supersonic wind tunnel (Mach 4)

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Kyushu Univ. Low Noise Wind Tunnel

Low Noise Test Section (No.1)

Göttingen type, in anechoic chamber

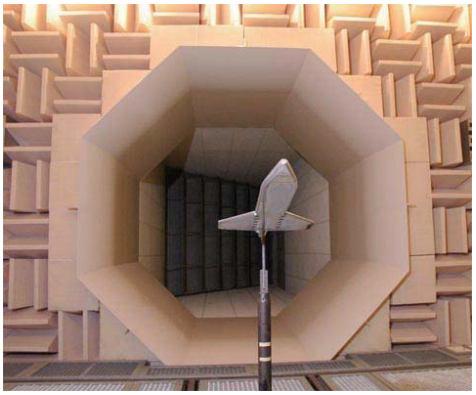
2 m width octagonal, 5 m length

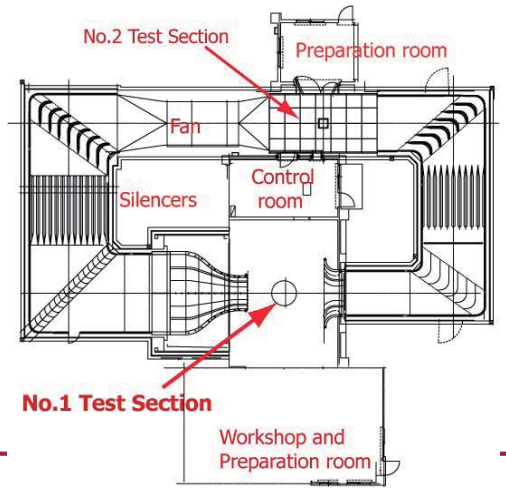
Max 60 m/s, 65 dB at 40 m/s

Large Closed Test Section (No.2)

3.5m x 3.5 m (max 15m/s),

30m/s with 3.5m x 1.5m insert





Space Transportation Systems Engineering Laboratory, Kyushu University

Kyushu Univ. Transonic Wind Tunnel

Blow down type Transonic wind tunnel

Mach 0.3～1.3

150mm x 450mm closed test section with slit walls

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Kyushu Univ. Supersonic Wind Tunnel

Blow down type Supersonic wind tunnel

- Mach 2.5 and 3.5
- 250x200mm closed test section

Kyushu Univ. Transonic Wind Tunnel

High enthalpy Flow test apparatus

- Free piston shock tunnel
- Detonation driven Expansion tube
- Normal Shock Tube

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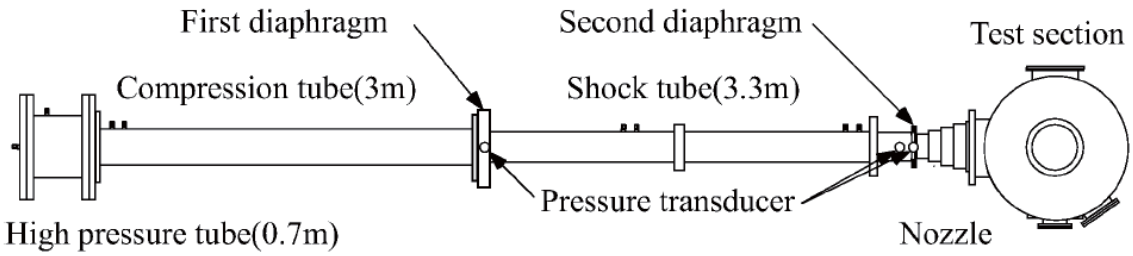
Free piston shock tunnel



High pressure tube : L 0.7 m, D 136.6 mm

Compression tube : L 3.0 m, D 70 mm

Piston : Mass 1.13 kg, L 49 mm

Shock tube : L 3.3 m, D 60 mm

Nozzle : Exit Diameter 270 mm,Area ratio 190, Design Mach 8

Test section : Volume 1m^3

CFD Tools

2D / 3D Navier-Stokes code (in house)

- Compressible Full Navier-Stokes / Euler
- Structured grid with Multi-Block formulation
- AUSM-DV scheme, LU-ADI
- Turbulence models
  - Wilcox k-ω 2eq. model
  - Spalart-Allmaras 1eq. model
  - Baldwin-Lomax algebraic model
- Chemical reaction

Grid Generation

- Gridgen
- Transfinite/Elliptic grid generator (In house)

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CFD Tools

Design tool

- PANAIR
- XFOIL
- Vortex lattice code
- Newtonian Flow code
- DATCOM

Background (1)

Space tourism market has been more active.

- VIRGIN GALACTIC
  - → Space Ship Two and White Knight Two
- ROCKET PLANE [GLOBAL]
  - → Rocket Plane XP

http://www.virgingalactic.com/

http://www.rocketplane.com/

New Technology and Development are required for Space Transportation System

Current Systems

‘Expendable Rockets’ & ‘Space Shuttle (partly reuse)’

High Economic Efficiency
Global Environment

Reusable Launch Vehicle（RLV）

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Background (2)

Considering the aerodynamic heating and structural weight

RLV's Wings are small compared with fuselages relatively

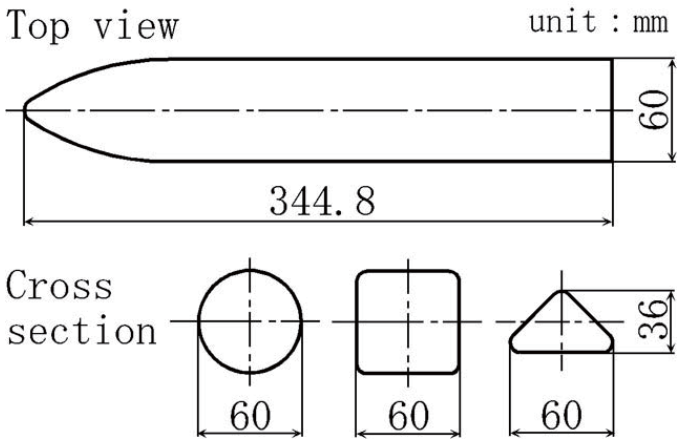
- Worse aerodynamic characteristics in subsonic region
- Fuselages have more effects on aerodynamic performance

Required aerodynamic characteristics & performance for RLV

- **High C_{Lmax}** ・・・ Low landing speed, rate of descent
- **High $(L/D)_{max}$** ・・・ Shallow flight path angle (Increment of downrange & cross range) Low rate of descent
- **Maneuverability, Safety, & Reliability**

Simplified fuselage models

Wind tunnel test models
- simplified fuselage model
- three different cross section



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Transonic and Supersonic Wind Tunnel

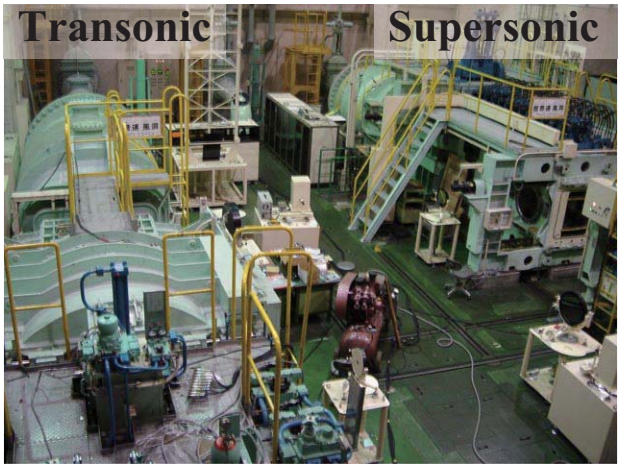
ISAS/JAXA Wind Tunnels

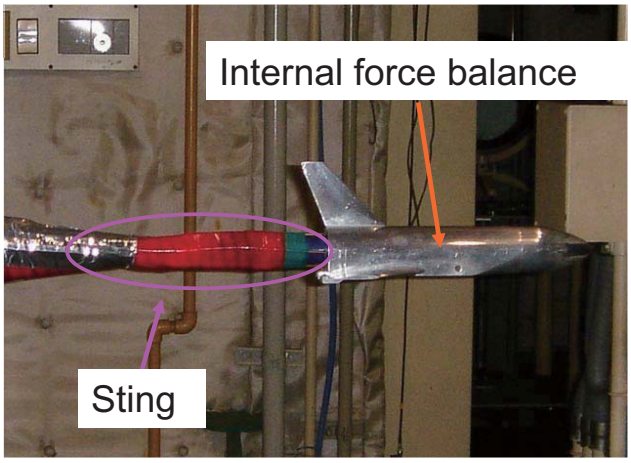
Transonic : $M_\infty = 0.3 \sim 1.3$

Supersonic : $M_\infty = 1.5 \sim 4.0$

Blow down type

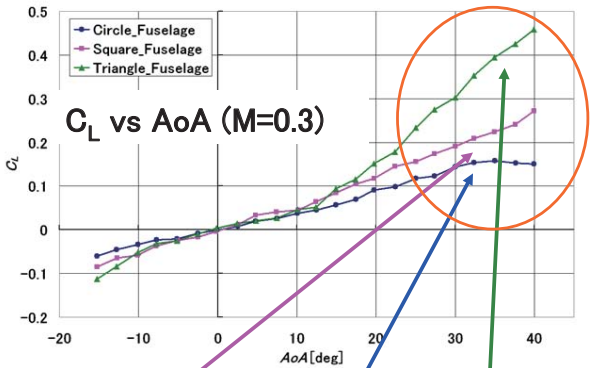
Test section : 600 mm × 600 mm

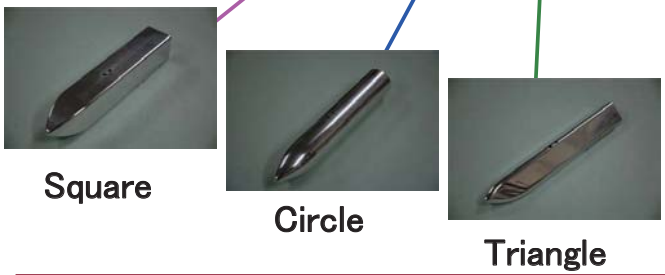


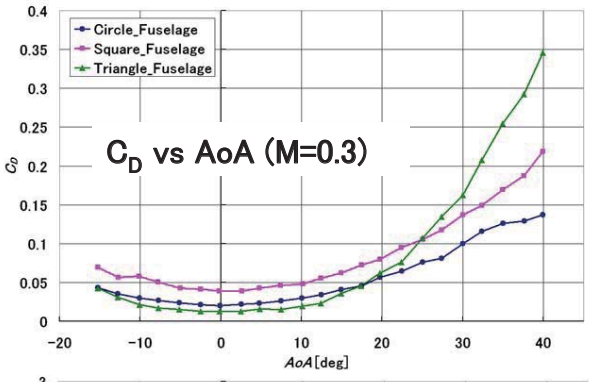


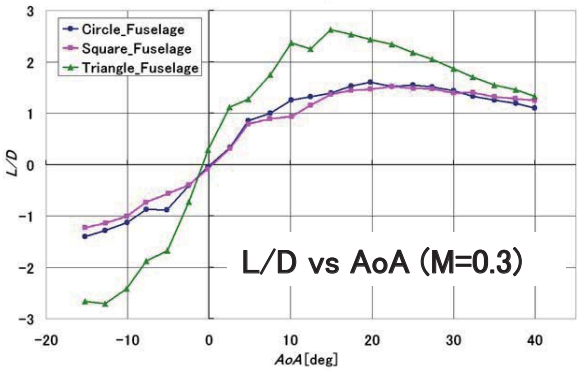
Wind tunnel test result (subsonic)

Significant differences on aerodynamic characteristics, highest Lift for triangle model.









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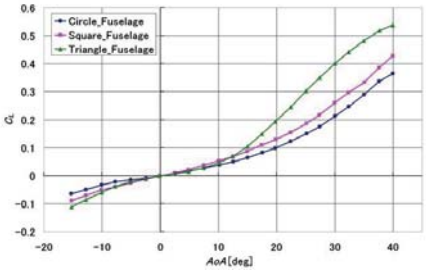
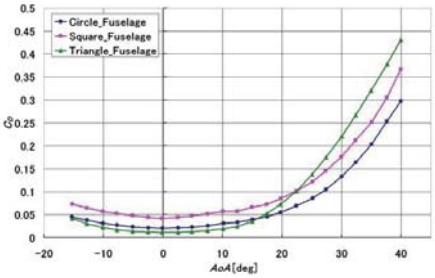
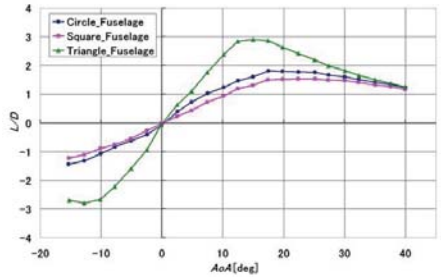
Wind tunnel test result (transonic)



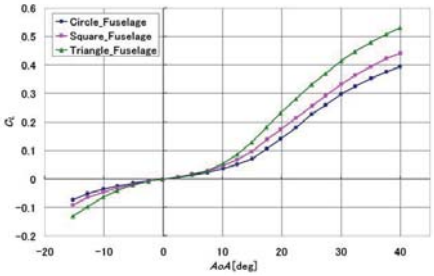
C_L vs AoA (M=0.9)



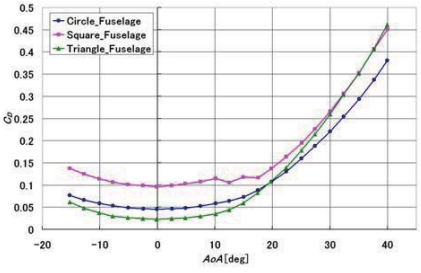
C_D vs AoA (M=0.9)



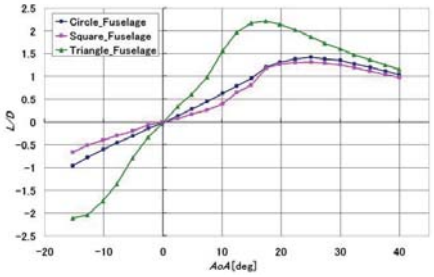
L/D vs AoA (M=0.9)



C_L vs AoA (M=1.3)



C_D vs AoA (M=1.3)



L/D vs AoA (M=1.3)

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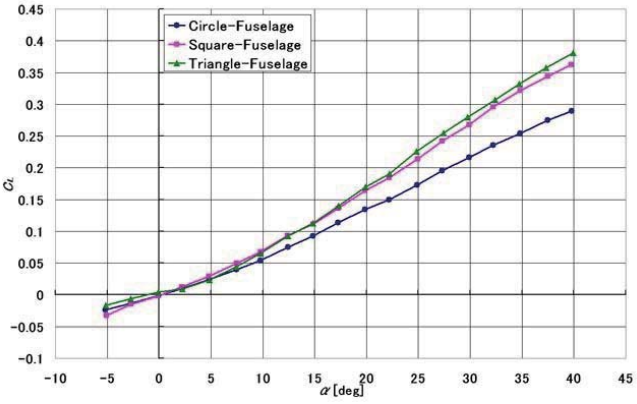
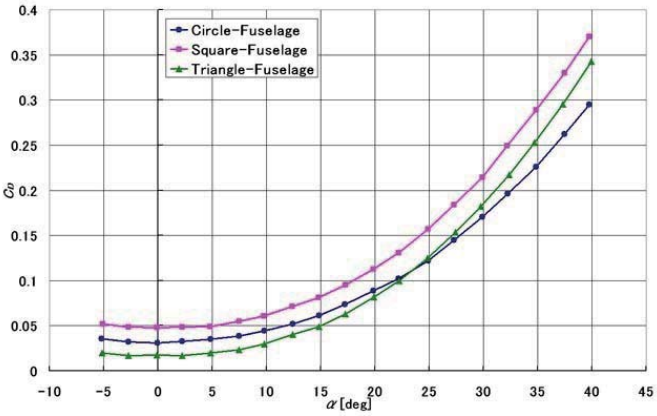
Wind tunnel test result (supersonic)

$M_\infty = 4.0$

$C_L - \alpha$ curves,



$C_D - \alpha$ curves



Cannot observe the significant differences on aerodynamic characteristics compared to subsonic region

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Wind tunnel test result (flow pattern)

[Top View]

Oil Flow Visualization (M=4.0, AoA=30deg)

Oil Flow Visualization (M=0.3, AoA=30deg)

Should be clarify the effect of the separated vortices on the aerodynamic forces

Numerical analysis : scheme

Governing Equation	3D Full Navier-Stokes Equation (RANS)
Convective terms	AUSM-DV scheme
Viscous terms	2nd order central difference
Time integration	Euler Explicit method
Turbulence model	k-ω two equation model

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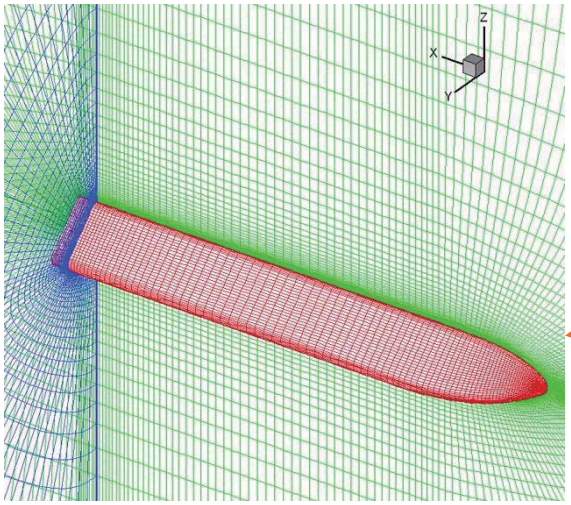
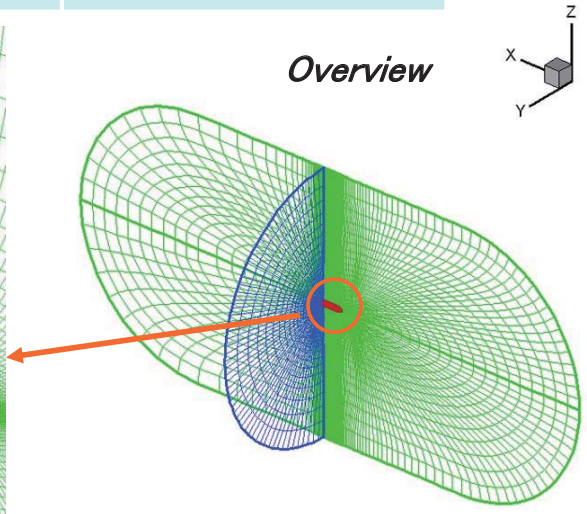
Flow condition and Computational Grid

Free Stream Mach Number	0.29
Total Pressure	1.51 × 10^5 Pa
Total Temperature	293.2 K
Angle of Attacks	30 deg



Overview



Grid Points : 167 × 70 × 59

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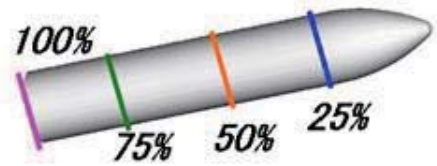
Comparison of CFD and Flow visualization

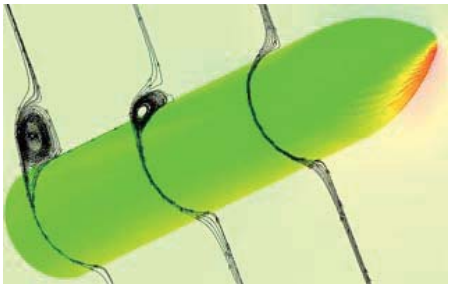
(Circle Fuselage, AoA=30deg)



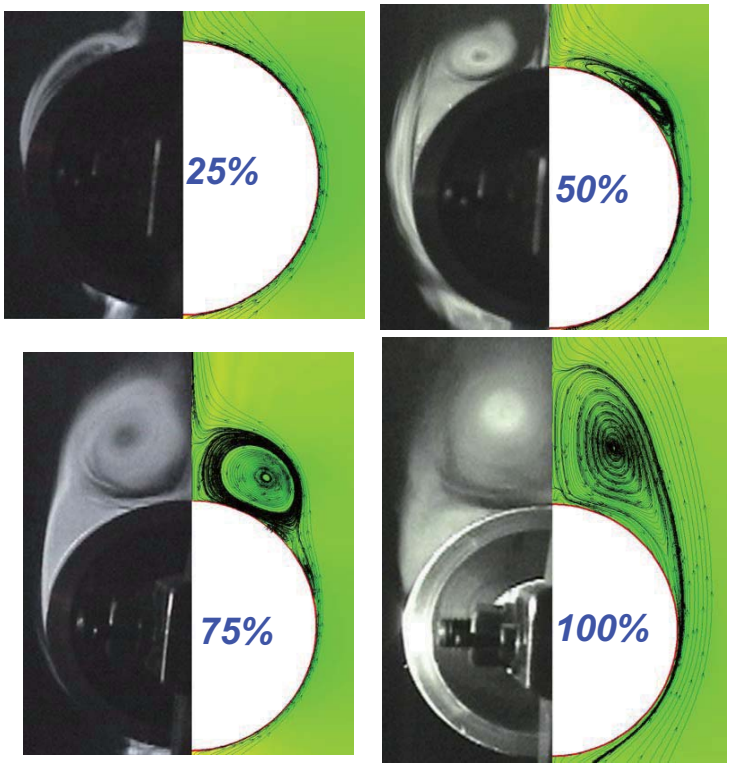
Aerodynamic Forces

Exp. : C_L=0.14, C_D=0.10

CFD : C_L=0.14, C_D=0.12



Growth of vortices & surface pressure



・ *Smoke : 3.5 m/s (Re=8.6×10⁴), CFD : M = 0.3 (Re=3.2×10⁶)*

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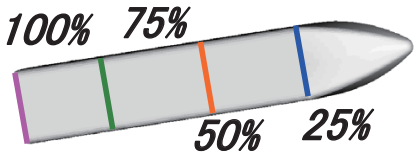
Comparison of CFD and Flow visualization

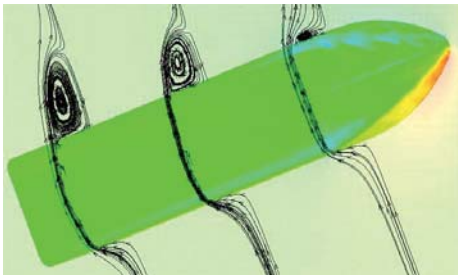
(Square Fuselage, AoA=30deg)



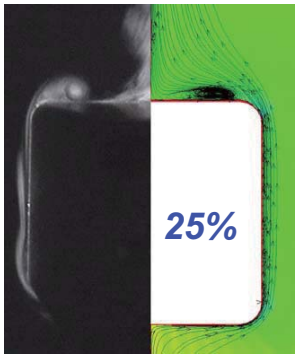
Aerodynamic Forces

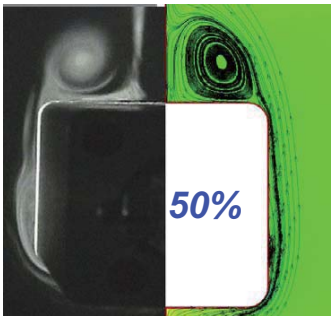
Exp. : C_L=0.19, C_D=0.14

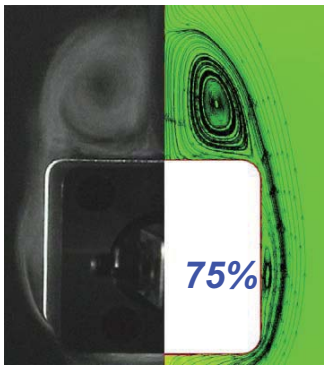
CFD : C_L=0.22, C_D=0.17

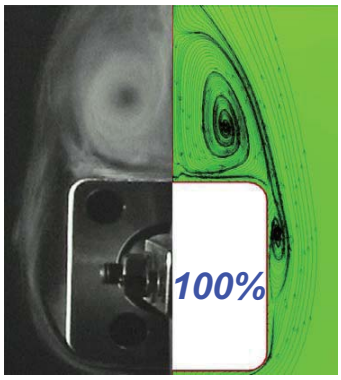


Growth of vortices & surface pressure



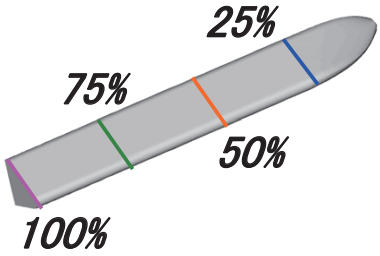






Comparison of CFD and Flow visualization

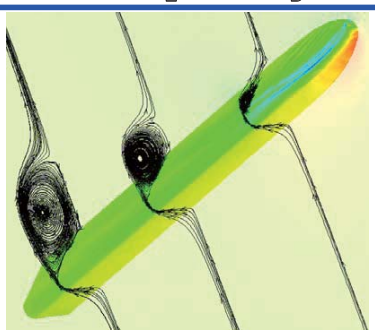
(Triangle Fuselage, AoA=30deg)



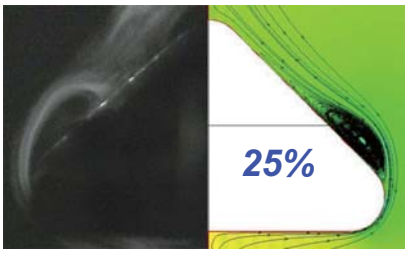
Aerodynamic Forces

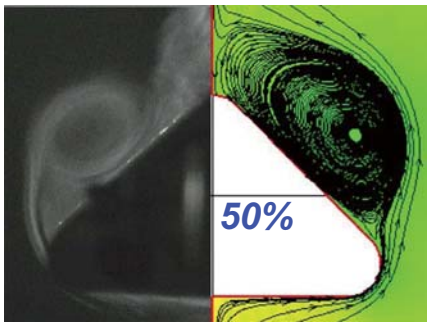
Exp. : C_L=0.30, C_D=0.16

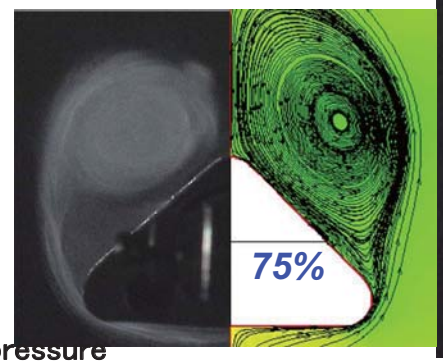
CFD : C_L=0.31, C_D=0.18

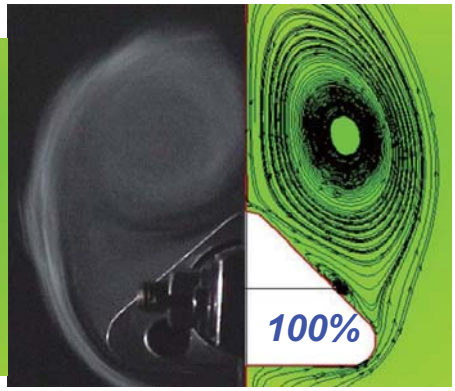


Growth of vortices & surface pressure









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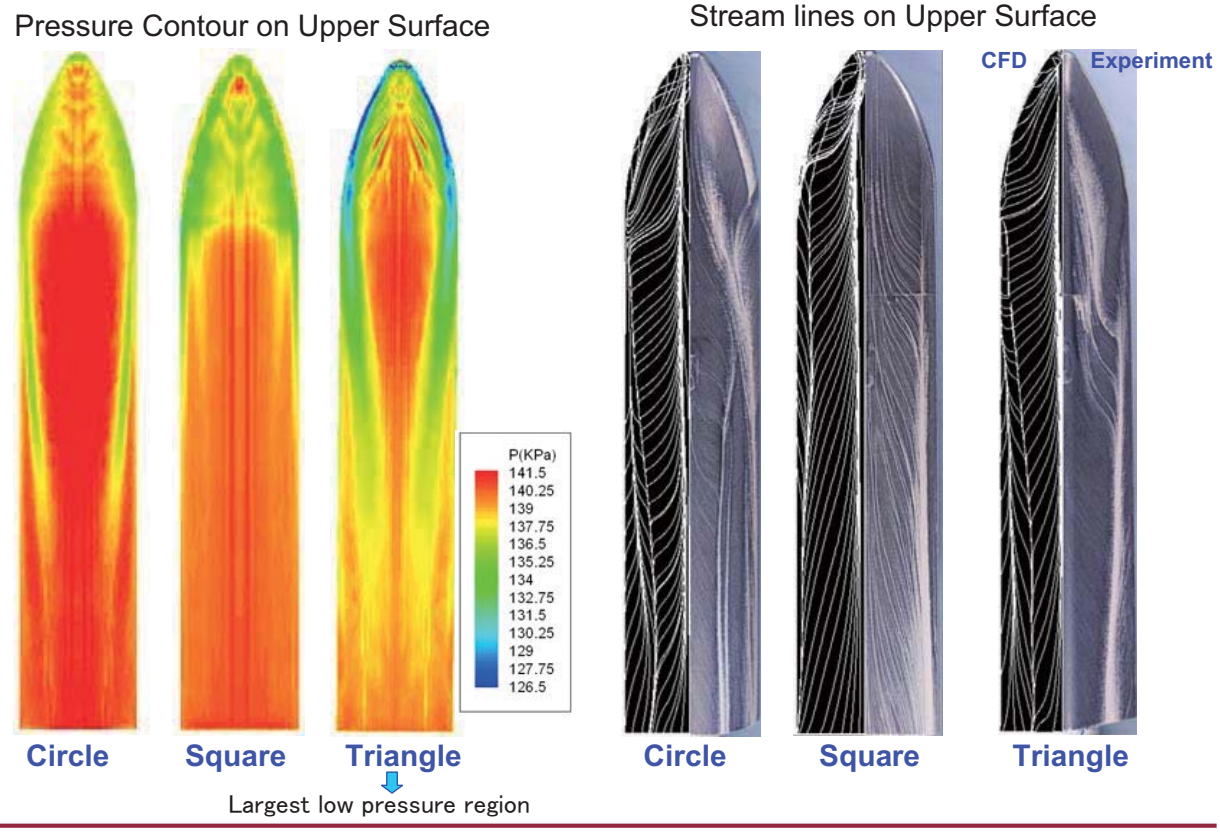
Stream lines on Upper Surface



Requirement for CFD

- higher accuracy for estimation of flow separation, aerodynamic forces, etc.
- reduction of computational time

Requirement for EFD

- improvement of wall interference correction, base drag correction, etc.
- spatial measurement
- non-contact measurement

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Background .. again

- In designing Reusable Launch Vehicle (RLV)
  → Aerodynamic Heating at reentry and supersonic flight

- Important Problems
  – Aerodynamic Heating at stagnation point
  – Increase of Aerodynamic Heating by transition of boundary layer

Courtesy of JAXA

Necessity of Aerodynamic Heating Reduction

Example of TPS

Courtesy of JAXA

Passive method

Heat absorption

Heat-resistant material

Active method

Mass transfer cooling

- Liquid
  - Transpiration cooling
- Gas
  - Film cooling
  - Cooling by opposing jet ← Nose region

Mechanical method

Intermediate method

Ablation

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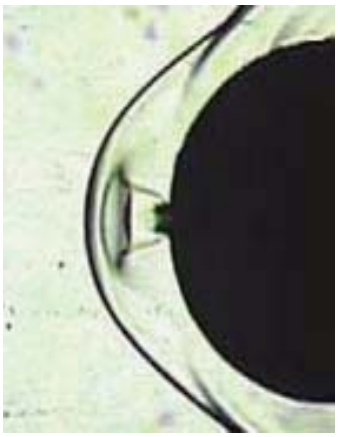
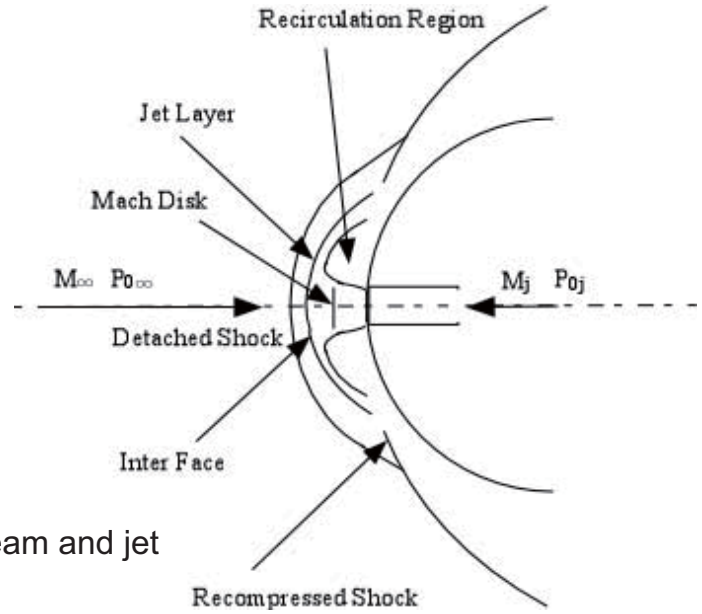
The Flow Field of the Opposing Jet





The governing parameters

- The Mach numbers of free stream and jet
- The diameter of the jet orifice
- The ratio of the total pressure of jet to that of free stream, PR

$$PR = \frac{p_{0j}}{p_{0\infty}}$$ the ratio of total pressure of opposing jet to that of free stream

Experimental Research

- Measurement of the heat flux
- Visualization of the flow field with Schlieren method
- Kyushu univ. supersonic wind tunnel

- **Free stream (average on exp.)**

Mach Number	3.96
Stagnation Pressure	1.37 MPa
Stagnation Temperature	397 K, 497 K
Reynolds Number	2.1×10^6

- **Secondary flow**

Mach Number	1.0
Total Pressure Ratio, PR	0.0 - 0.8
Stagnation Temperature	300 K

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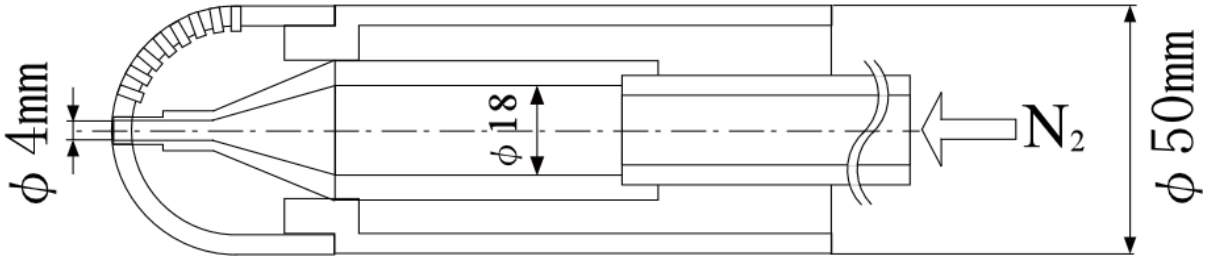
Experimental model : blunt body



- The diameter of the model : 50 mm
- The diameter of the jet orifice : 4 mm
- Mach number at the jet orifice : 1.0

- The calorimeter gauges are attached at 20 to 90 degrees (every 10 degrees)
- The model is installed into the free stream after the flow becomes steady flow.

Numerical Analysis Method

- Governing Equation: Reynolds averaged axisymmetric Navier-Stokes equation (RANS)
- Time Integration : LU-ADI method
- Convection Term: AUSM-DV scheme with MUSCL interpolation
- Viscous Term: 2nd-order central difference scheme
- Turbulence model : k-ω two equation model
  - C_μ term is introduced in order to prevent the excessive generation of *k* in collision region. Craft et.al(1996).

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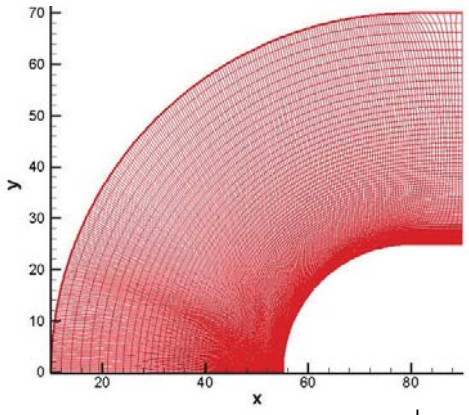
Flow Conditions and Grid for supersonic flow

<Main flow>	
Mach number	3.96
Total pressure [MPa]	1.37
Total temperature [K]	397
<Secondary flow>	
Mach number	1.0
Pressure ratio	0, 0.4, 0.6, 0.8
Total temperature [K]	300
<Wall condition>	
Wall temperature [K]	295

• Grid (242 × 160)

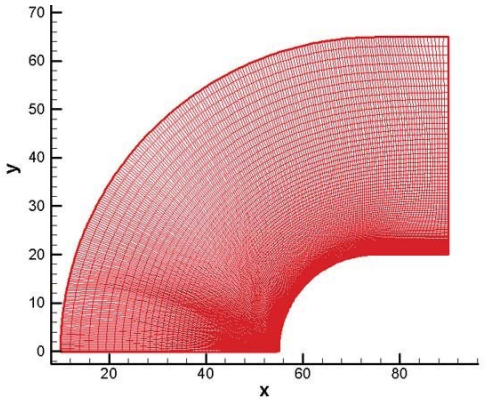


Diameter of body [mm]	50
Diameter of jet orifice [mm]	4

Flow Conditions and Grid for hypersonic flow

<Main flow>	
Mach number	8.0
Total pressure [MPa]	4.5
Total temperature [K]	800
<Secondary flow>	
Mach number	1.5
Pressure ratio	0.0251~0.0859
Total temperature [K]	300
<Wall condition>	
Wall temperature [K]	300

• Grid (240 × 160)



Diameter of body [mm]	40
Diameter of jet orifice [mm]	4.34

■ This flow conditions and grid configuration are based on the experiment conducted by Tokyo Univ. in 1975.

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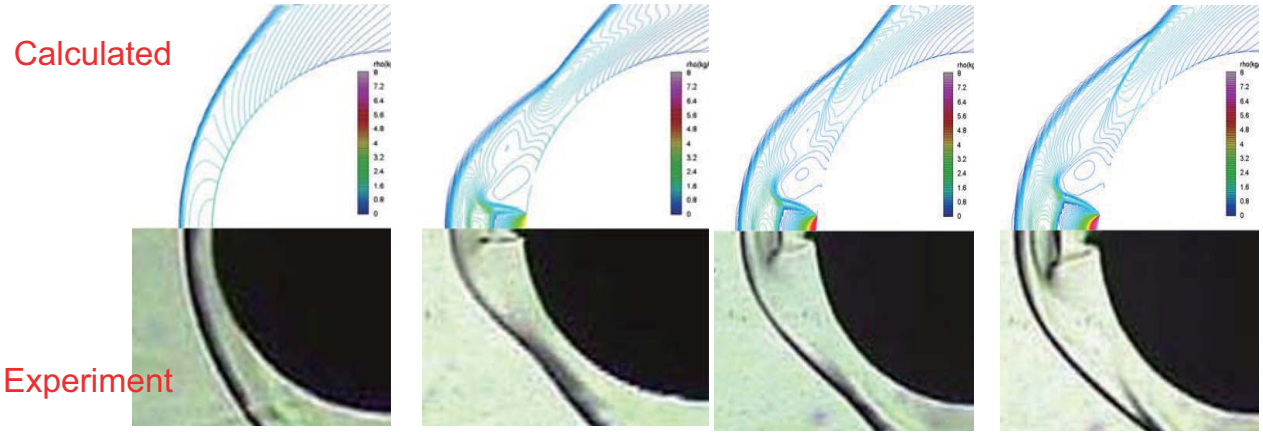
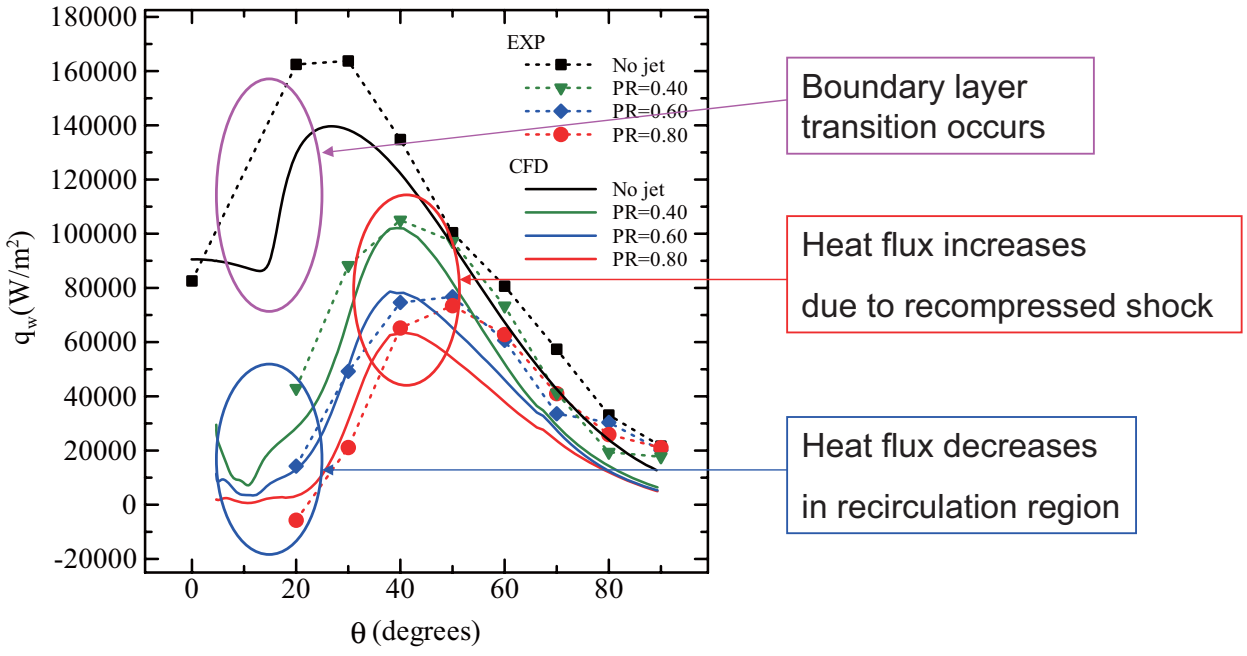
Flow field at each PR (Mach 3.96)



Comparison of Heat Flux (Mach 3.96)



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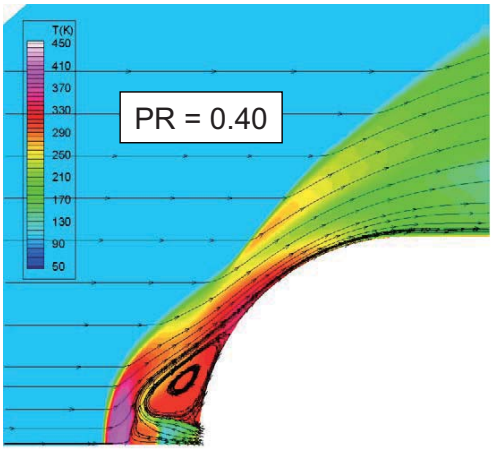
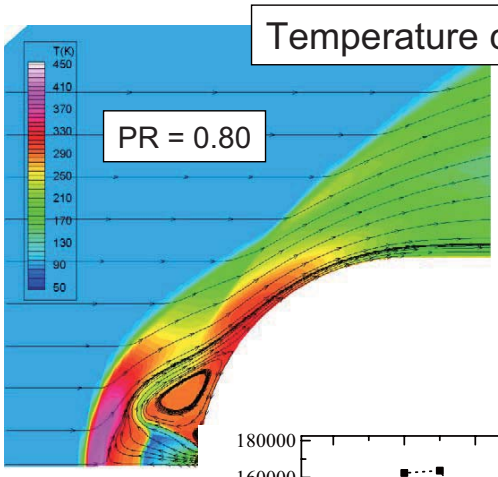
Flow field change by PR (Mach 3.96)

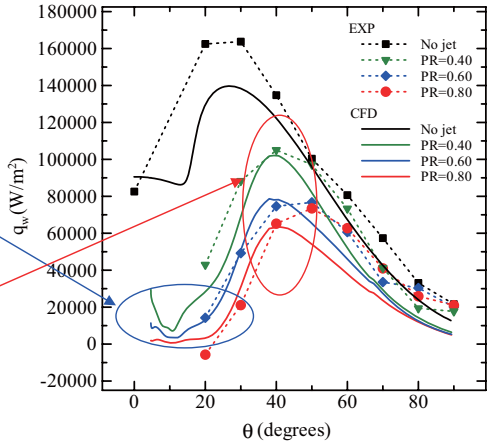




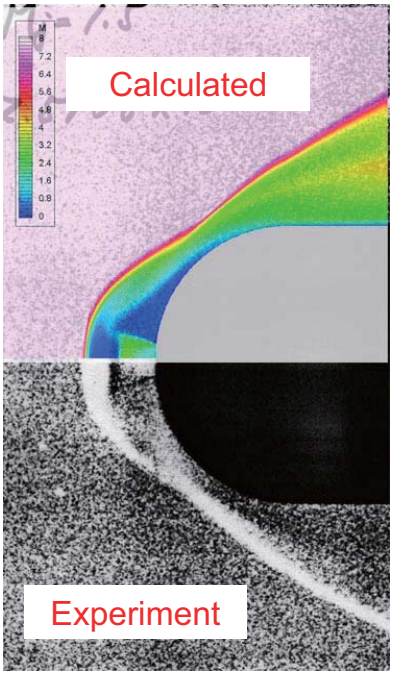
Temperature contour

Heat flux decreases in recirculation region

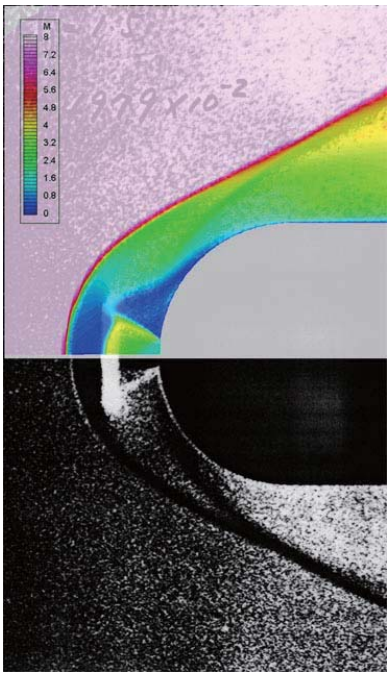
Heat flux increases due to recompressed shock



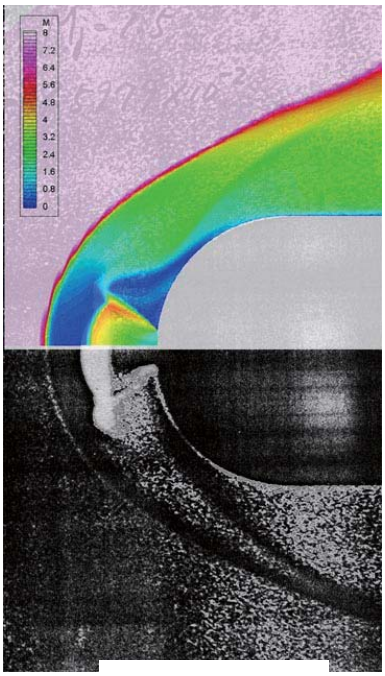
Flow Field at each PR (Mach 8)



PR=0.0251



PR=0.0549



PR=0.0859

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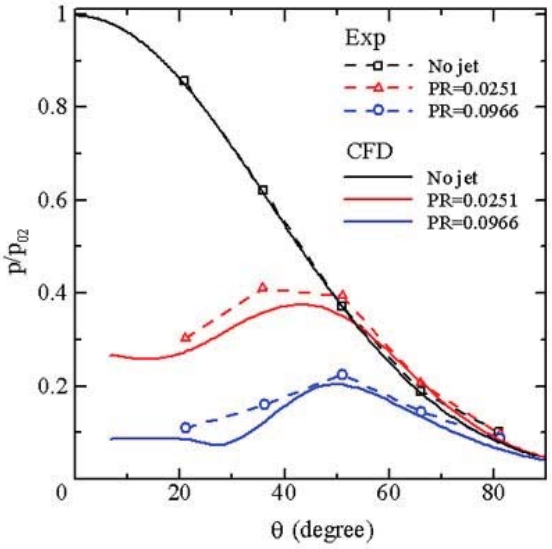
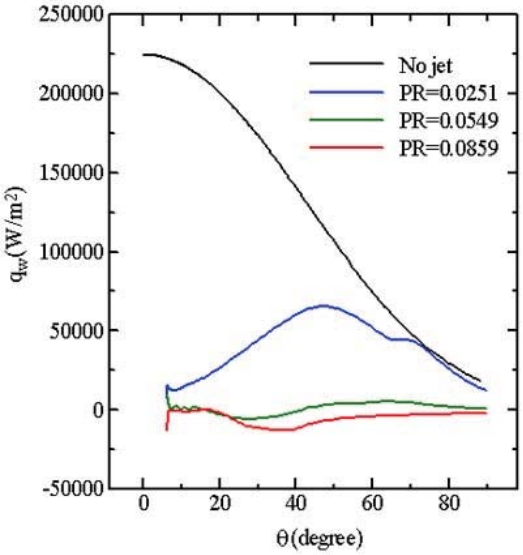
Pressure Distributions (Mach 8)

Pressure Distributions



- CFD pressure distribution shows good agreement with experimental measurement.

Heat Flux Distributions (CFD)



- Heat flux decreased more considerably than the case for supersonic.
- Heat flux at each angles decreased as PR increases.

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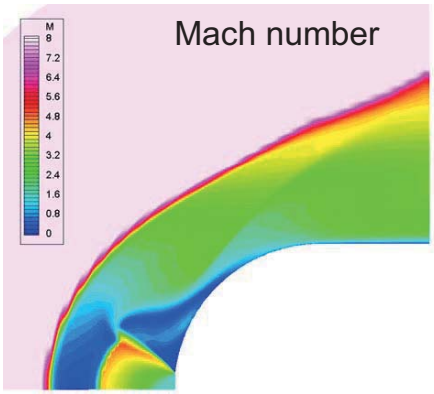
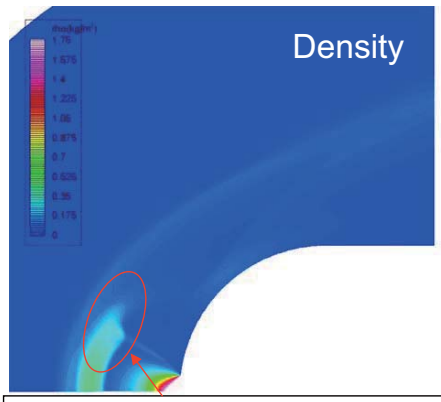
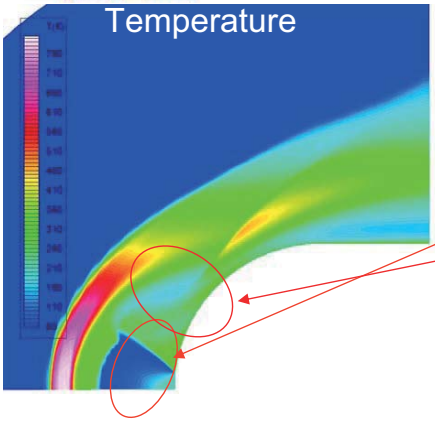
Understanding the flow field





Mach 8
PR=0.0859



- High density in stagnation region
  - ⇩ Large heat capacity
- Low temperature jet
  - ⇩
- Low temperature recirculation region
  - ⇩
- Remarkable reduction of aerodynamic heating

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Consideration

- The opposing jet is useful to reduce aerodynamic heating in supersonic and hypersonic flow.
- To understand the mechanism of reducing aerodynamic heating by the opposing jet, detailed flow field should be clarified.
- CFD is very powerful tool to understand the flow field, but has to be validated.

Background .. Once again

Development of scram-jet engine is now in progress as a propulsion system of hypersonic transports and space planes.

⇩

・In scram-jet engine, the speed of air is very high. Hence rapid mixing and combustion of air and fuel is required. (Air residence time in combustor is 10^{-3}～10^{-4} sec)
・At high Mach number, suppression of development of shear layer occurs and it makes mixing of air and fuel difficult .

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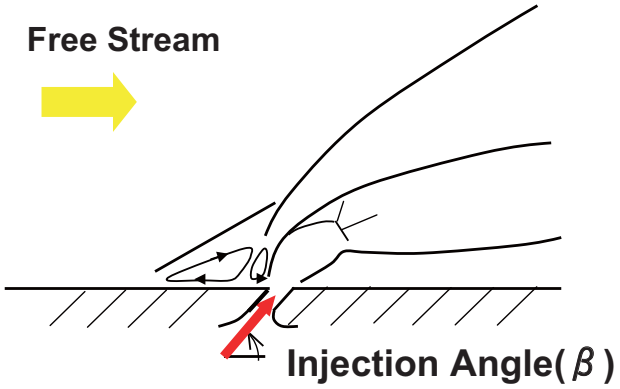
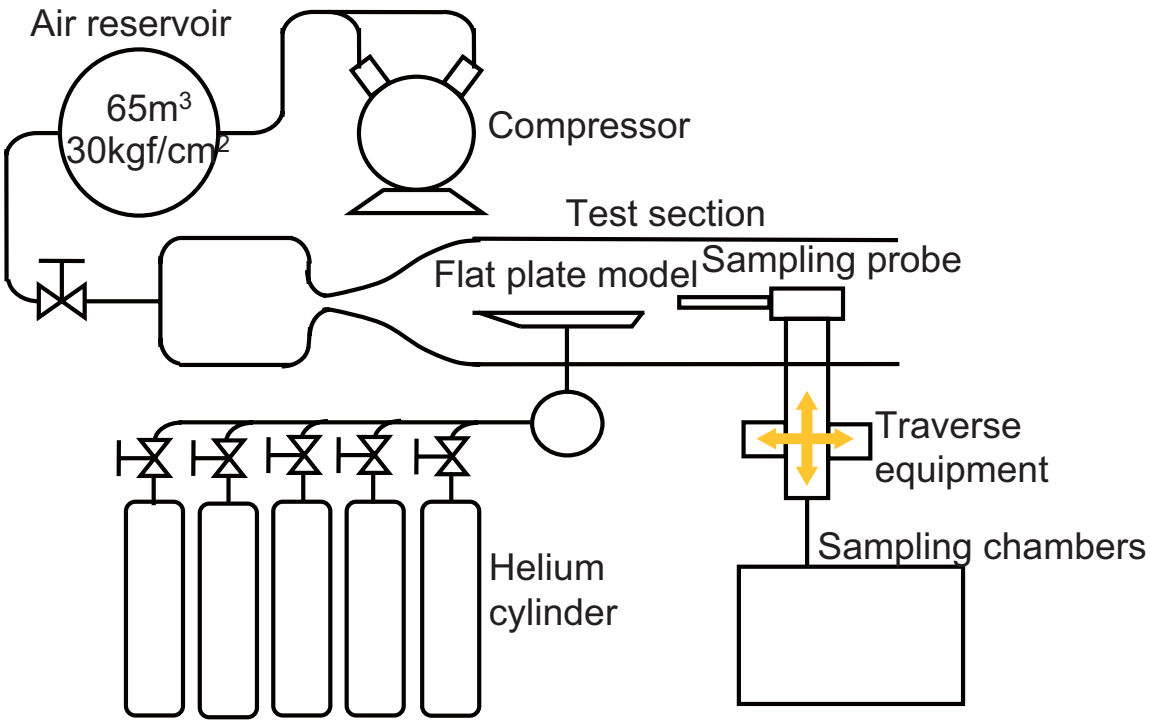
Objective of the present study

Investigation of the effect of the injection angle β of three-dimensional circular nozzle on supersonic mixing flow



Schematic of experimental facility



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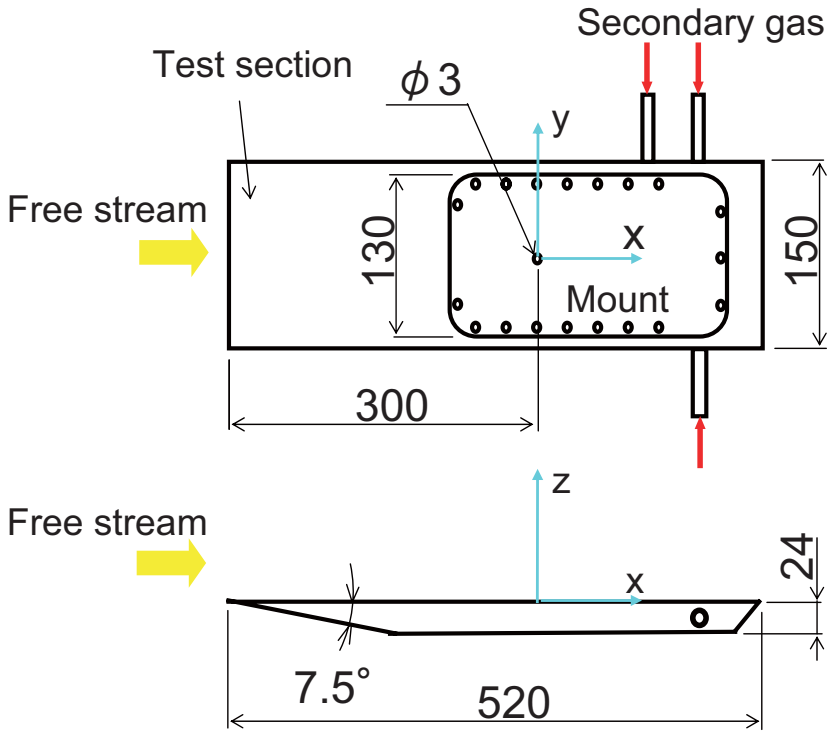
Schematic of the experimental model



Experimental conditions

Free stream	Gas	Air
	Mach number	3.76
	Total pressure	1. 12 MPa
	Total temperature	286.9 K
Secondary gas	Gas	Helium
	Mach number	1.0
	Total pressure	0.40 MPa
	Total temperature	286.9 K

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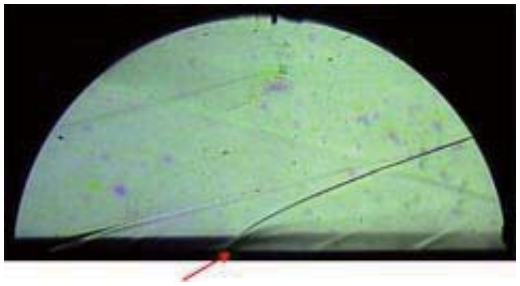
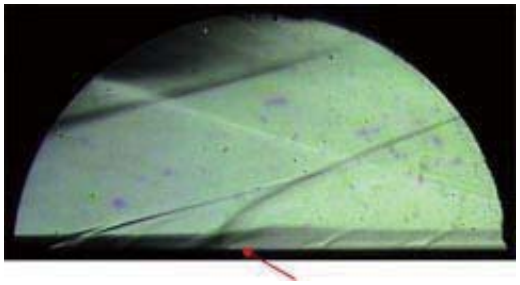
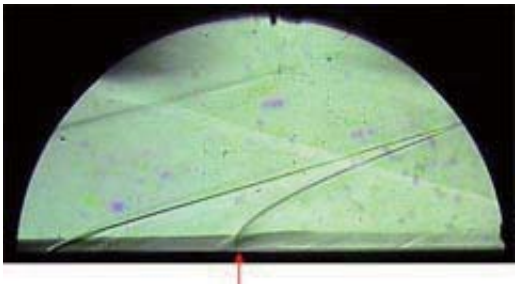
Flow visualization by Schlieren method



(a) β =30°



(c) β =150°



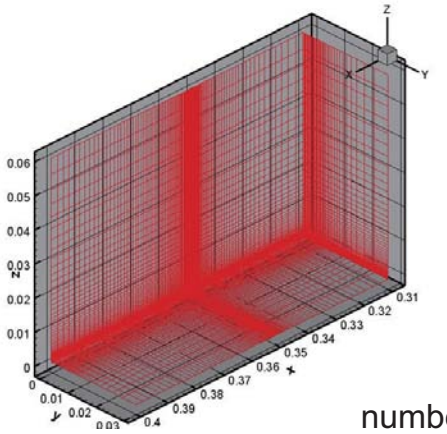
(b) β =90°

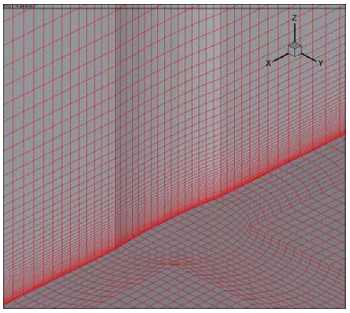
- separation shock wave
- bow shock wave

As injection angle β becomes large, separation region becomes wider and bow shock wave becomes stronger.

Numerical method

Governing equations :	Reynolds averaged 3D full N-S
Convective terms :	AUSM-Plus scheme
Viscous terms :	2nd order central difference
Time integration :	LU-ADI method
Turbulence model :	k-ω two equation model
	with Low Reynolds number effect





number of grid point : 116×42×75

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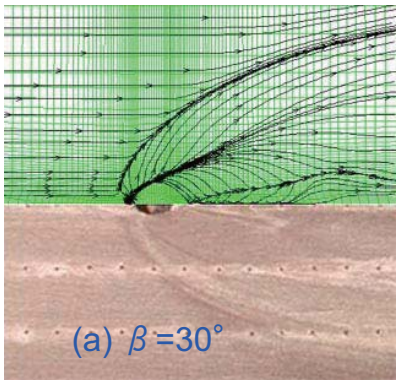
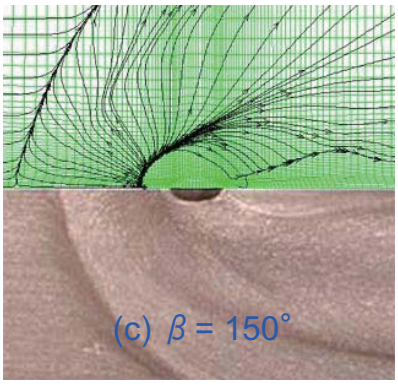
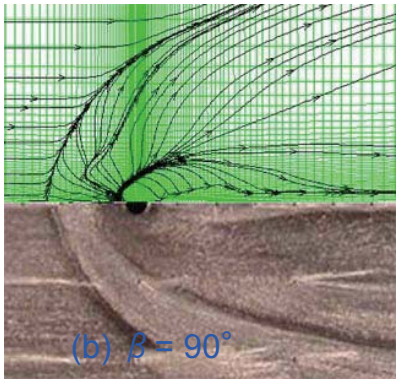
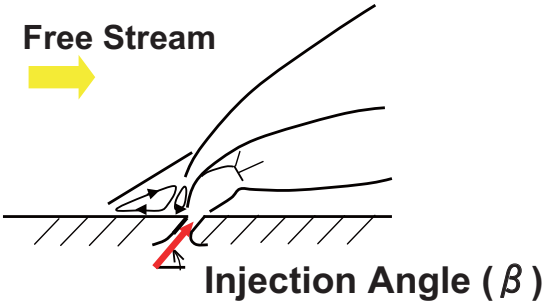
Stream line on surface

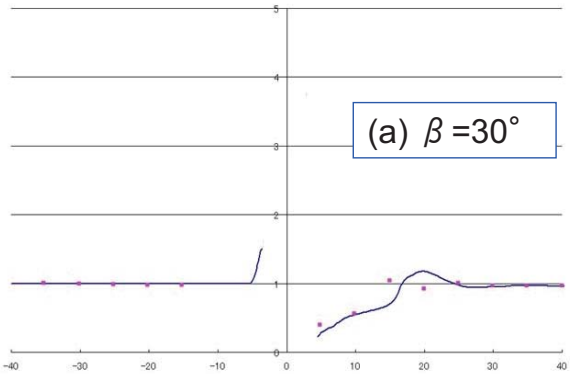


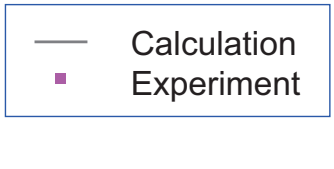


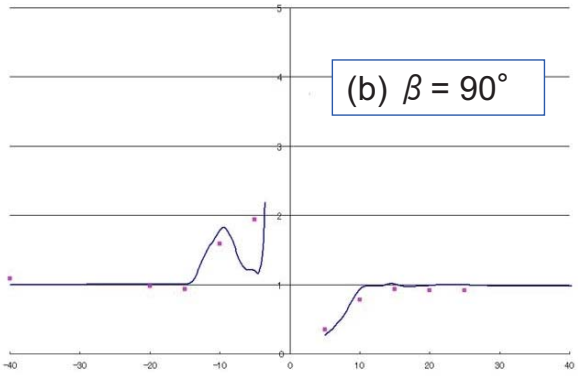


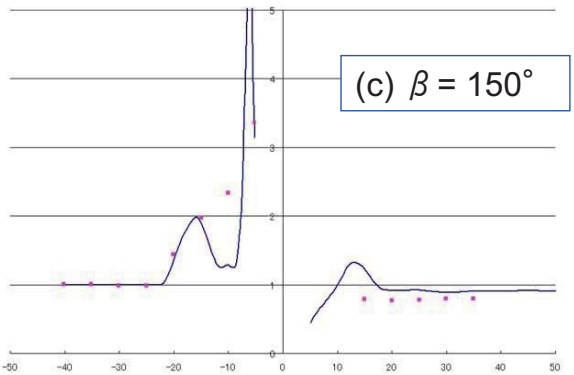


Wall pressure distribution at y=0









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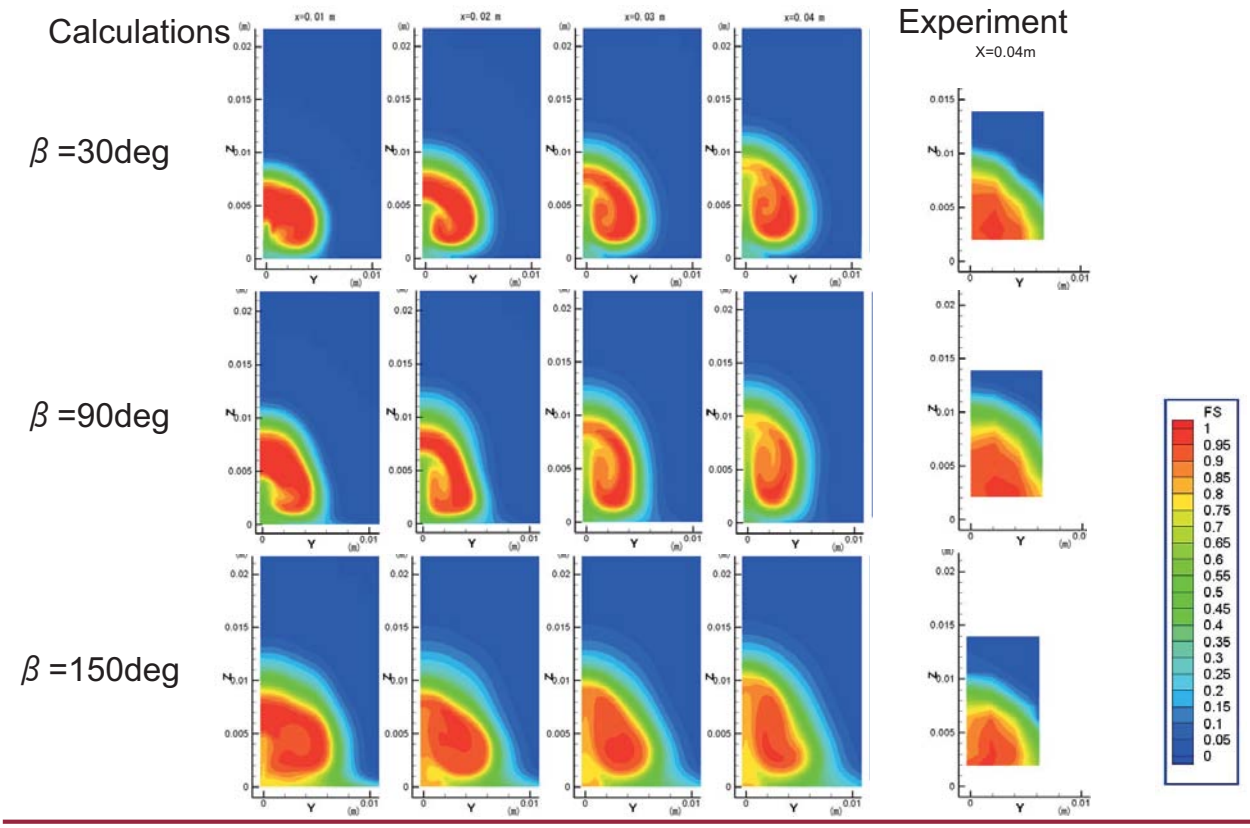
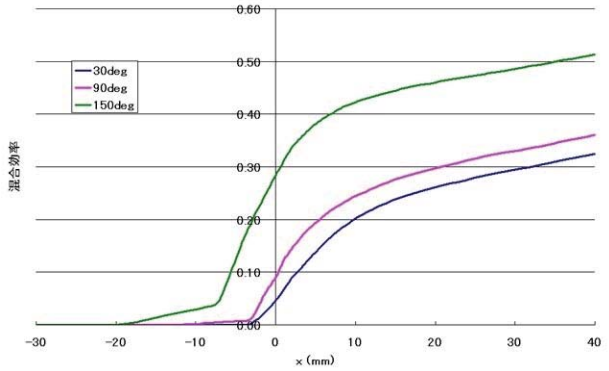
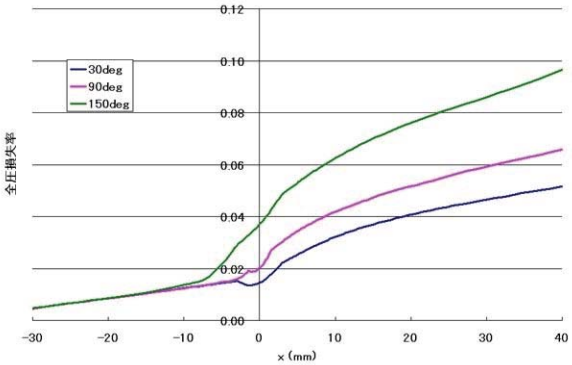
Volume fraction distribution



Mixing efficiency and Total pressure loss





$$\eta(x) = \frac{\int_A \frac{\rho u f_{H_2}}{\Phi} dA}{\int_A \rho u f_{H_2} dA}$$

$$\Phi = \begin{cases} 1 & (\text{if } \phi(x,y,z) \le 1) \\ \phi(x,y,z) & (\text{if } \phi(x,y,z) > 1) \end{cases}$$

$$\phi(x,y,z) = 35 \times \frac{f_{H_2}}{1 - f_{H_2}}$$

Stoichiometric mass ratio ... Hydrogen : Air = 1 : 35

A : Cross section of test section
f_{H_2} : Mass fraction of hydrogen
ϕ : Local equivalent ratio in the cross section dA

$$\pi(x) = 1 - \frac{\int_{A(x)} \rho u p_t dA}{\int_{A_i} \rho u p_t dA + \int_{A_j} \rho u p_t dA}$$

p_t : Local total pressure
A : Cross sectional area at *x*
A_i : Cross sectional area at the entrance of the test section
A_j : Cross sectional area of the injector

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Considerations

1) Supersonic mixing phenomena can be fairly simulated not only in separated region but also in mixing.
2) Flow characteristics for injection angles shows good agreements between CFD and experiments.
3) Detailed measurement of flow field and reliability of CFD should be improved.

Conclusions

EFD and CFD in a university,

Research Education

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Second Workshop on Integration of EFD and CFD
24th Feb 2009, JAXA

Static Aeroelasticity Analyisis of AGARD-B Wind Tunnel Calibration Model Using Discontinuous Galerkin CFD Solver

Kanako YASUE*
and
Keisuke SAWADA

* Ph.D Student, Graduate School of Engineering,
Dept. of Aerospace Engineering, Tohoku University, JAPAN

Prediction of Aerodynamic Characteristic

- Accurate prediction of aerodynamic characteristics
  - Affected by boundary layer transition and separation
  - Required wind tunnel test with actual flight Re number
- Conventional wind tunnel test
  - 1 or 2 order lower Re number compared with actual flight due to model size restriction or facility restriction
  - Putting roughness to promote turbulent transition at lower Re number
  - Extrapolation of the aerodynamic performance in actual flight from wind tunnel data (Re number scaling effect)

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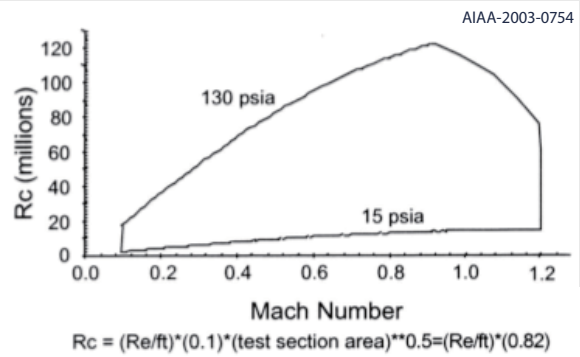
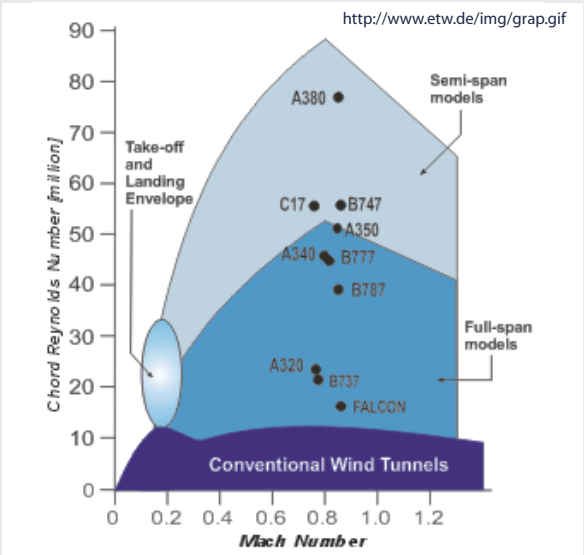
High Re Number Wind Tunnels

- National Transonic Facility (US, 1982)
- European Transonic Wind-tunnel (Germany, 1993)
  - High Re number comparable to that of actual flight environment
  - Lowering temperature of pressurized airflow to that of cryogenic level



NTF performance envelope



ETW performance envelope

03

Features of High Re Number Wind Tunnel

- Highly pressurized airflow
- Larger aerodynamic load on the model
- Model deformation of thin part
- Altering aerodynamic features
- Masking Re number scaling effect

In NTF and ETW

- Independent control of total pressure and total temperature
- Separate evaluation of Re number effect and model deformation effect

04

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High Re Number Wind Tunnel in Japan

- Trisonic Wind Tunnel (Japan, 2005)
  - Highly pressurized airflow (P_{0max}=1.4 MPa, Re_{max}=1x10^8 /m)
  - Cannot control total pressure and total temperature independently
  - Cannot isolate Re number scaling effect and model deformation effect

Accurate prediction of aerodynamic performance in TWT

- Isolation of model deformation effect using CFD
- Small change in geometry of wind tunnel model causes small change in aerodynamic performance

  ⇒ High-order CFD schemes

05

Objectives

- Explore effect of model deformation in TWT by fluid-structure interaction analysis
  - Static aeroelasticity analysis of AGARD-B wind tunnel calibration model
    - CFD analysis : Discontinuous Galerkin (DG) method

      ⇒High order spatial accuracy on unstructured mesh
    - Structural analysis : NX/NASTRAN®
  - Examination of model deformation and its influence to aerodynamic characteristics

06

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Discontinuous Galerkin Method

$$\iiint_{\Omega} w(\mathbf{x}) \left(\frac{\partial Q}{\partial t} + \nabla \cdot \mathbf{F}(Q) \right) d\Omega = 0$$

$$Q(\mathbf{x},t) = \sum_j Q_j(t) v_j(\mathbf{x})$$

$$w(\mathbf{x}) \leftarrow v_i(\mathbf{x})$$

$w(\mathbf{x})$: test function

$Q_j(t)$: degree-of-freedom (DOF)

$v_j(\mathbf{x})$: basis function (Jacobi polynomial)

$$\sum_j \frac{dQ_j}{dt} \iiint_{\Omega} v_i v_j d\Omega + \iint_{\partial\Omega} v_i \mathbf{F}(Q) \cdot \mathbf{n} d\sigma - \iiint_{\Omega} \mathbf{F}(Q) \cdot \nabla v_i d\Omega = 0$$

- Basis functions and dependent variables become discontinuous at cell interface
- Numerical flux is given by approximate Riemann solver
- Viscous term is discretized using BR2 formulation

Pointwise Relaxation Implicit Scheme

- Flux function is solely expanded by the change of DOFs in own computational cell
- Resulting algebraic equation is pointwise

$$\mathbf{F}^{n+1} \cong \mathbf{F}^n + \frac{\partial \mathbf{F}^n}{\partial Q} \Delta Q = \mathbf{F}^n + \frac{\partial \mathbf{F}^n}{\partial Q} \sum_j v_j \Delta Q_j$$

$$\sum_j \frac{dQ_j}{dt} \int_{\Omega} v_i v_j d\Omega + \int_{\partial\Omega} v_i \mathbf{F}^{n+1}(Q_h) \cdot \mathbf{n} d\sigma - \int_{\Omega} \mathbf{F}^{n+1}(Q_h) \cdot \nabla v_i d\Omega = 0$$

$$\mathcal{M}^n \Delta Q_j = \mathcal{R}^n$$

size of $\mathcal{M}^n$ = [(# of Dependent variables)×(# of DOFs)]^2

$$\mathcal{M}^n = \frac{1}{\Delta t} \sum_j \int_{\Omega} v_i v_j d\Omega + \sum_j \int_{\partial\Omega} v_i \left(\frac{\partial \mathbf{F}^n}{\partial Q} \cdot \mathbf{n} \right)^+ v_j d\sigma - \sum_j \int_{\Omega} v_i \left(\frac{\partial \mathbf{F}^n}{\partial Q} \nabla v_i \right) v_j d\Omega$$

$$\mathcal{R}^n = - \int_{\partial\Omega} v_i \mathbf{F}^n(Q_h) \cdot \mathbf{n} d\sigma + \int_{\Omega} \mathbf{F}^n(Q_h) \cdot \nabla v_i d\Omega$$

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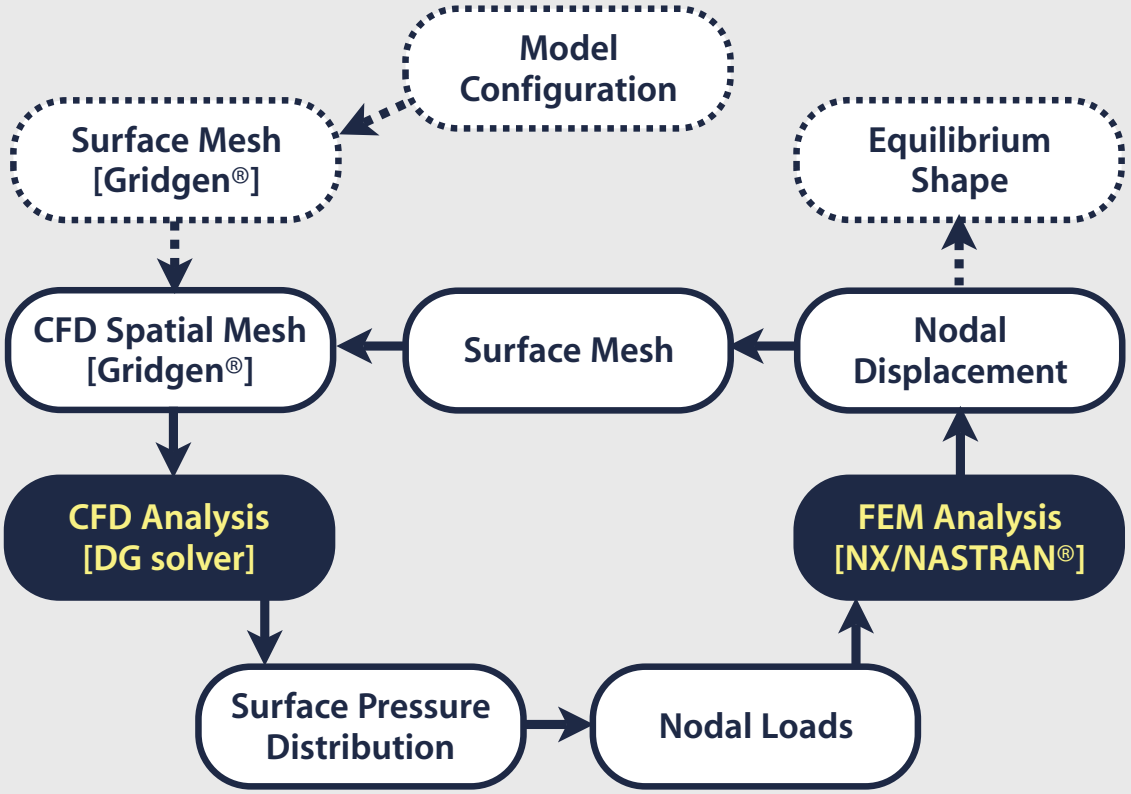
Aeroelasticity Analysis Procedure



09

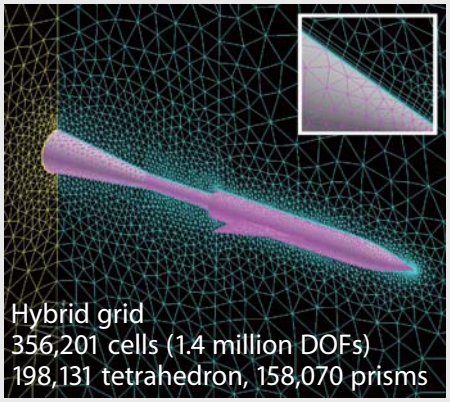
Supersonic Flowfield over AGARD-B Model

Numerical Schemes

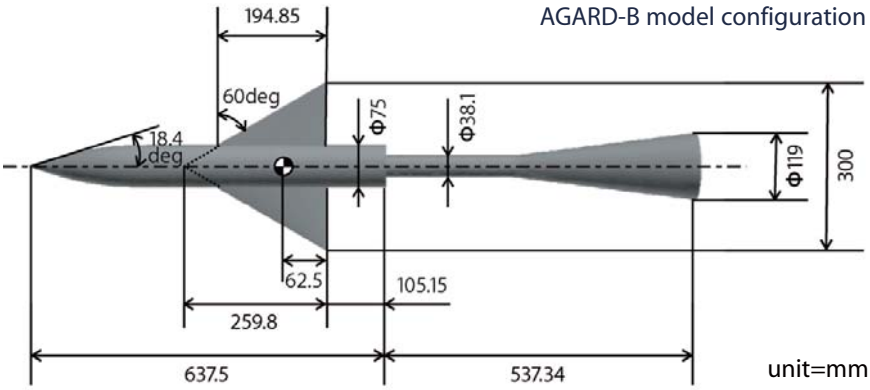
- RANS equations
- 2nd order DG method
- Pointwise relaxation implicit scheme
- AUSM-DV upwind scheme
- BR2 formulation
- Spalart-Allmaras turbulence model
- Slope limiter
- CFL=10^5

Parallelization

- METIS grid partitioning
- MPI Library
- Xeon Dual Core 3.0GHz x2 (4cores)



AGARD-B model configuration



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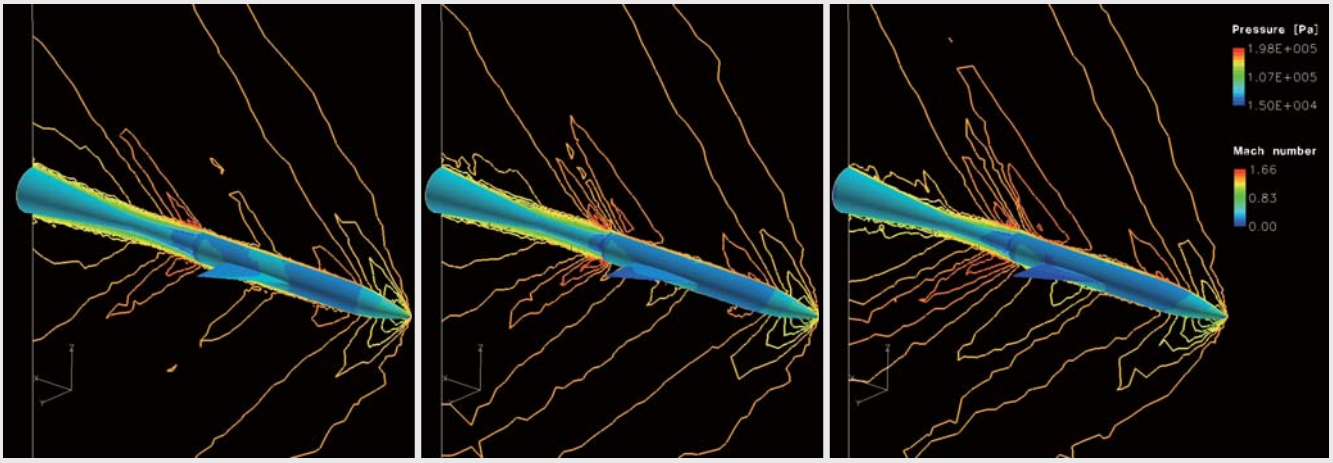
Flow Conditions (TWT)

	Mach number	Angle of Attack [deg]	Side Slip Angle [deg]	Re number x10^6 [1/m]	Total Pressure [kPa]	Total Temperature [K]
Case1	1.4	0.098	-0.005	27.6	167.1	276.4
Case2	1.4	4.303	-0.003	27.8	167.0	274.5
Case3	1.4	8.535	-0.001	27.9	167.1	273.9

Pressure and Mach Number Contours

Baseline Computations

Case1 (α=0.09) Case2 (α=4.30) Case3 (α=8.53)



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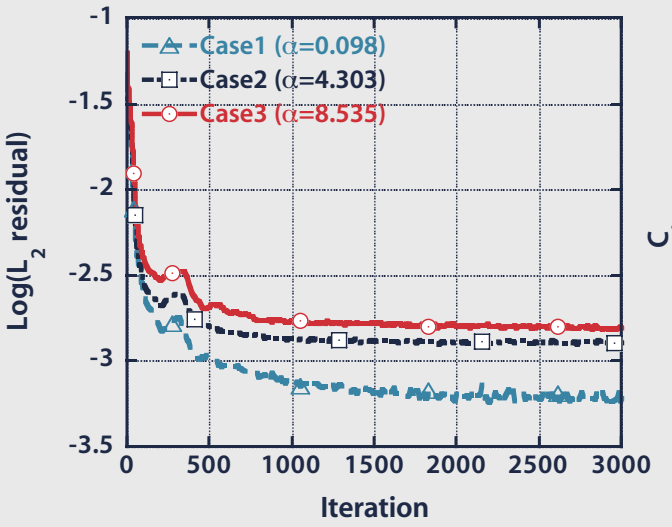
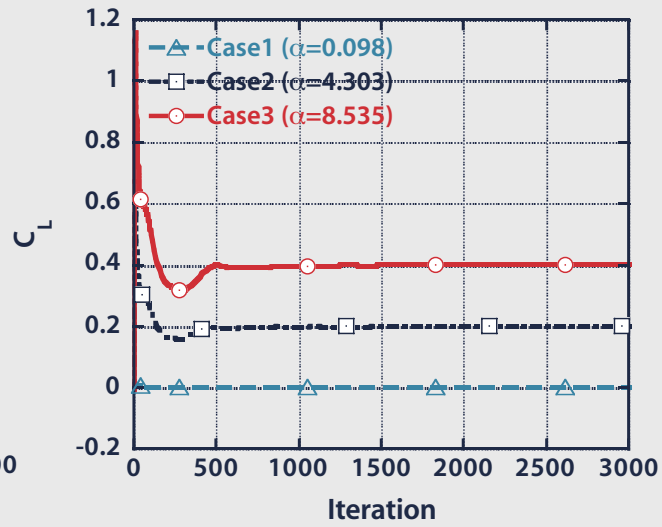
Convergence Histories

Baseline Computations





- L_2 residual and C_L are converged within 3000 iterations
- L_2 residual decreases only for 2 orders of magnitude

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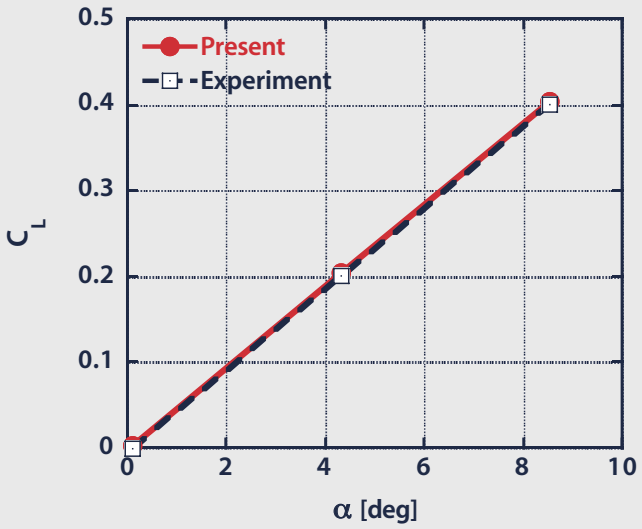
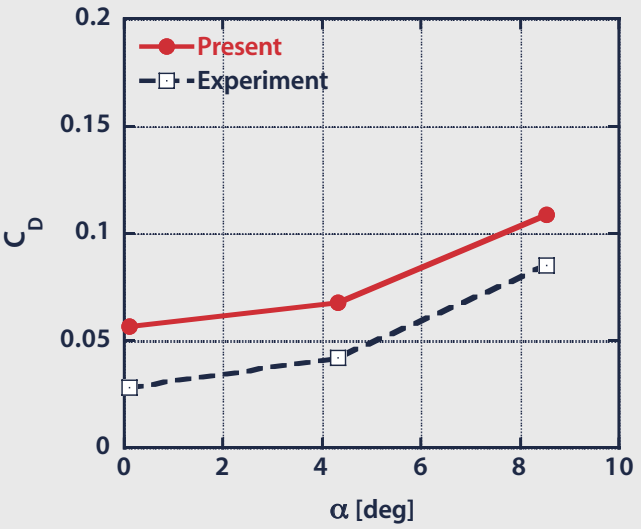
Aerodynamic Coefficients

Baseline Computations





- Using finer mesh and considering effect of turbulence transition at trip location will be needed

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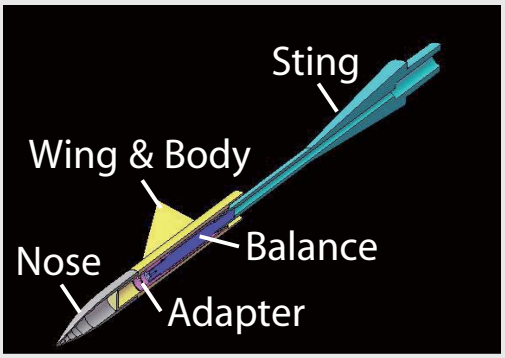
Aeroelasticity Analysis of AGARD-B Model

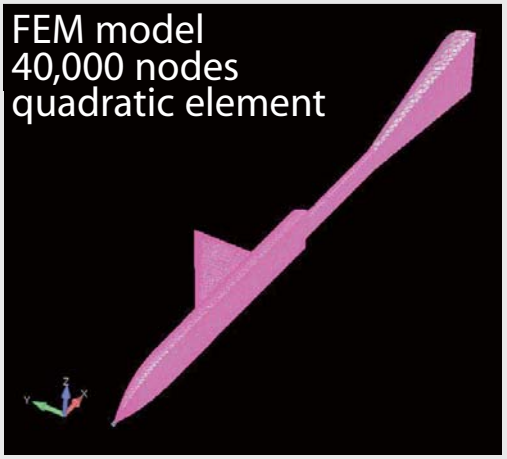
Structural computation by NX Nastran

- SUS304
- Same surface mesh with CFD
- Nodal load data converted from steady state CFD solution at surface boundary
- Fixed condition at root plane boundary

Flowfield computation

- RANS equations
- 2nd order DG method
- Pointwise relaxation implicit scheme
- AUSM-DV upwind scheme
- BR2 formuration
- Spalart-Allmaras turbulence model
- Slope limiter
- CFL=10^5





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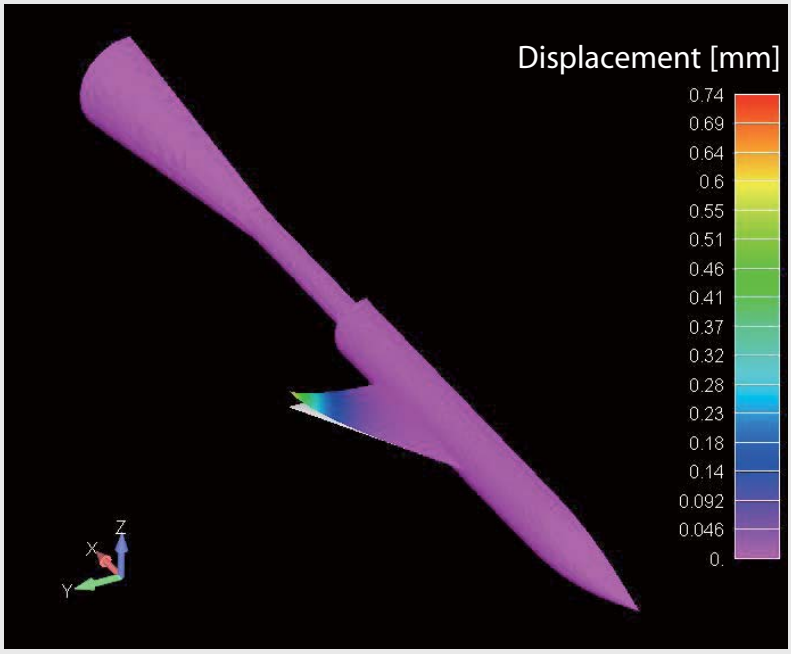
Obtained Model Deformation



- Model deformation analysis is only considered for Case3 (α=8.5)
- Maximum wing tip displacement is 0.737 mm

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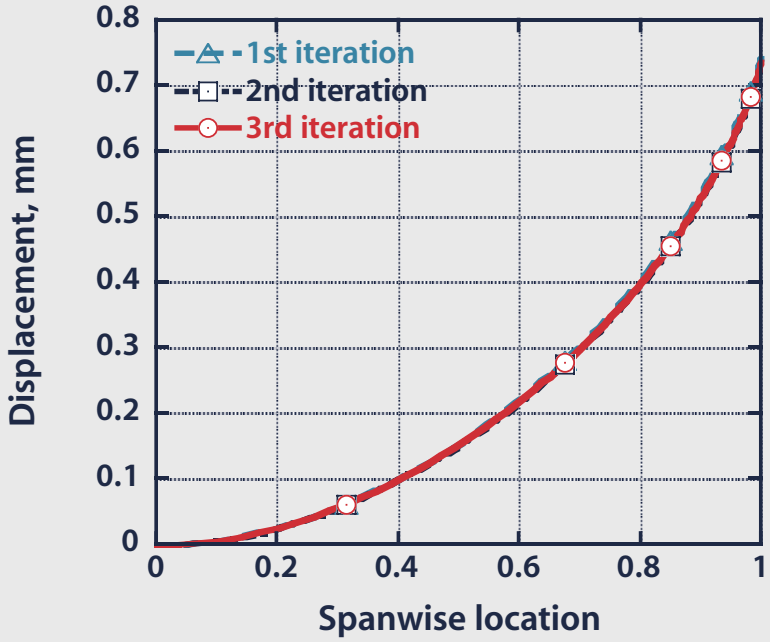
Converged Deformation along Trailing Edge



- Convergence is obtained only within 3 iterations in this case

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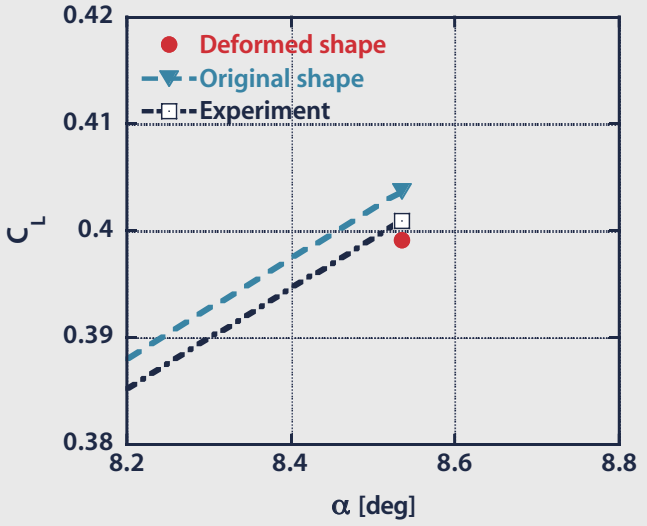
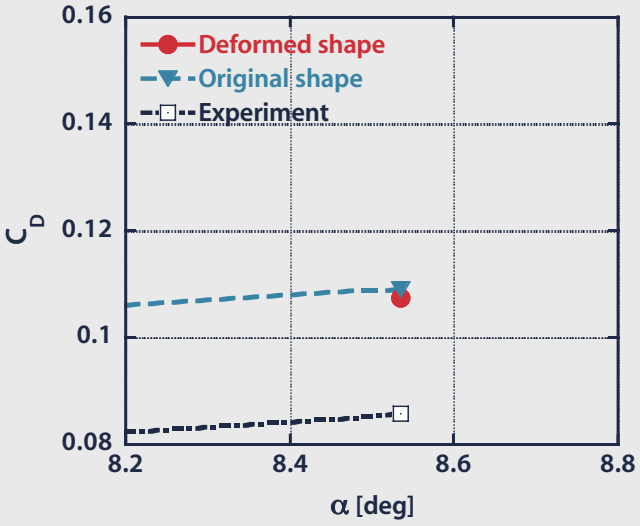
Aerodynamic Characteristics





- C_L decreases 0.0047 due to model deformation
- C_D decreases 0.0018 due to model deformation
- Even for small displacement, resulting change in aerodynamic coefficient cannot be ignored

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Concluding Remarks

- The aeroelasticity analysis of AGARD-B wind tunnel calibration model is successfully carried out
  - Pointwise relaxation implicit discontinuous Galerkin method for flowfield computation is coupled with NX/NASTRAN for structural analysis
  - Maximum deformation of wing tip is less than 1mm
  - ΔC_L and ΔC_D due to model deformation cannot be ignored
  - DG solver is suitable for static aeroelasticity analysis
- Effect of model deformation should be isolated in experimental data of TWT for higher Re number conditions

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Future Works

- Computation using finer mesh and considering turbulent transition at the trip location
- Higher order approximation and boundary representation for flowfield computation
- Considering internal structure for elasticity analysis
- Constructing techniques to isolate Re number effect and model deformation effect in TWT

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Prediction of Wake Turbulence under Actual Atmospheric Condition

Hiroshi Kato, Takashi Misaka, Shigeru Obayashi
(Institute of Fluid Science, Tohoku University, Japan)
Izumi Yamada
(Electronic Navigation Research Institute, Japan)
Yoshinori Okuno
(Japan Aerospace Exploration Agency, Japan)

Second Workshop on Integration of EFD and CFD
February 23-24, 2009 (Chofu, Japan)

Outline

- Background
  - Wake turbulence
  - Data assimilation for realistic environmental simulation
  - Data utilization in CFD and NWP
  - Toward prediction of wake turbulence
- Objective of this research
- Approach for wake turbulence simulation
  - Doppler lidar at Sendai airport
  - Attempt to predict of wake turbulence
- Results
  - Retrieved background wind field
  - Behavior of a vortex pair in assimilated wind field
- Conclusions

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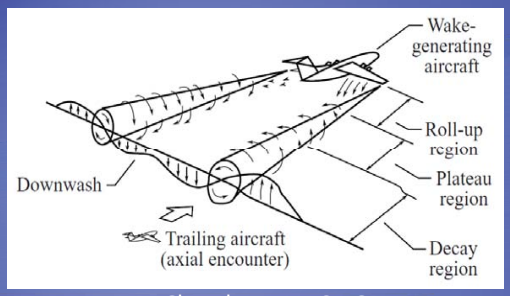
Background -Wake turbulence-



J. R. Chambers, NASA SP-2003-4529

Discovery Channel

Wake turbulence

■ Wake turbulence, which generated two vortices from wing tip stay behind, is dangerous for a following aircraft.

■ Strength of wake turbulence is proportional to the lift and the inverse of velocity. That is, wake turbulence is most strong at takeoff and landing conditions, especially in the case of a heavy aircraft.

$$\Gamma = \frac{L}{\rho V b}$$

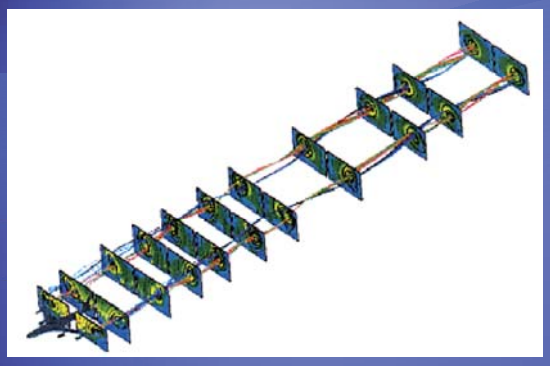
L: lift, ρ: air density
V: velocity, *b*: wing span

Wake turbulence-related accidents

■ There were 3 accidents during the past half decade in Japan, and 200 accidents during the past two decades in the United States.

Background -Need for realistic conditions-

Calculation of whole aircraft

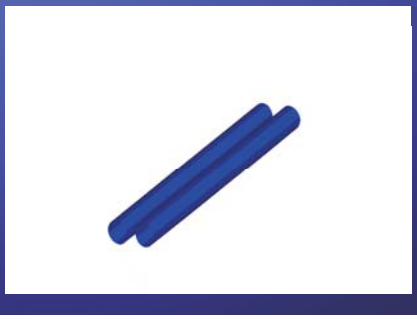


K. Hueneche, AIAA2001-2427

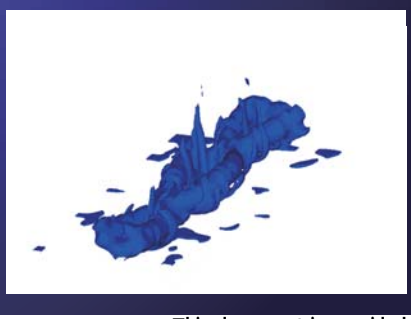
- Detailed analysis of wake turbulence's behavior
- Difficulty in incorporating actual condition

➢Disturbance in a flow field significantly affects the decay of wake turbulence

Without turbulence



With turbulence



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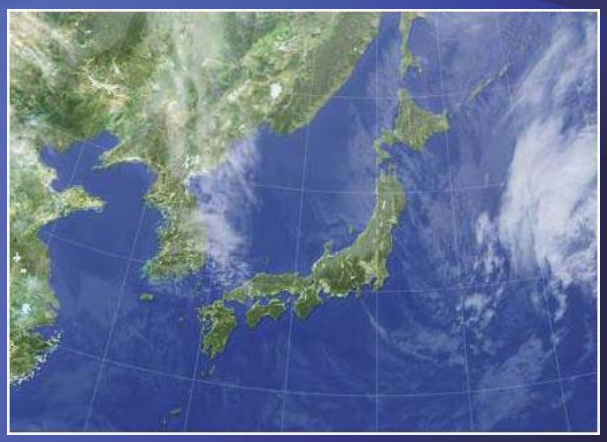
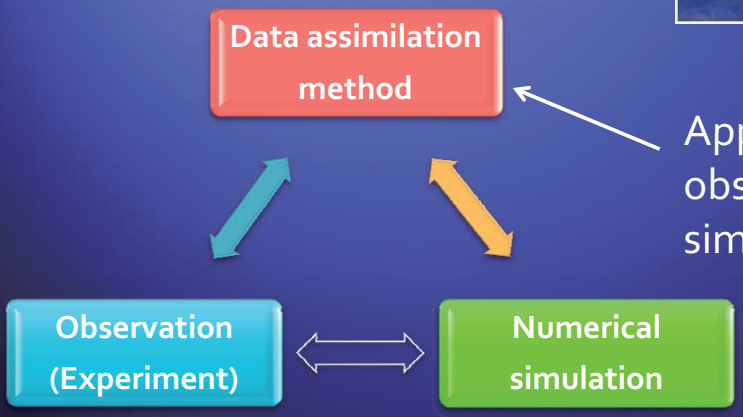
Background -Data assimilation method-

- Developed in meteorological and oceanic from the 1990s onward
- Method for accurately estimating the complex time evolutional system, such as atmosphere, with observations (experiments) and a numerical model





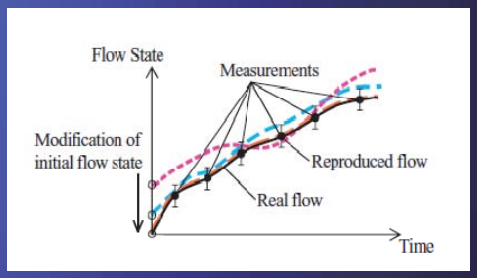
Approach method to integrate observation and numerical simulation research

Background

-Two major approach for data assimilation-

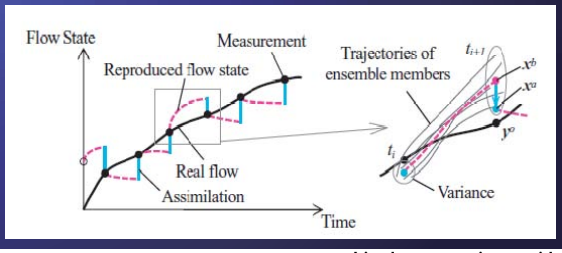
Variational approach
(e.g. four-dimensional variational method)

- Initial flow state is modified based on measurements within certain period of time



Sequential approach
(e.g. ensemble Kalman filter)

- Flow field is modified when measurement are obtained



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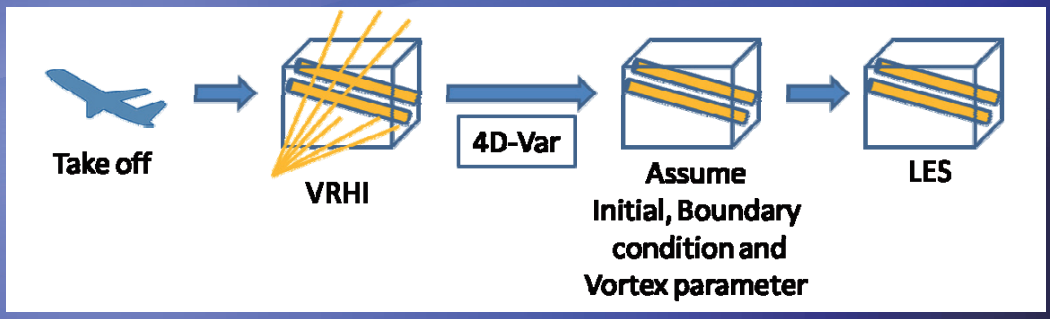
Back ground - Data utilization in CFD and NWP -

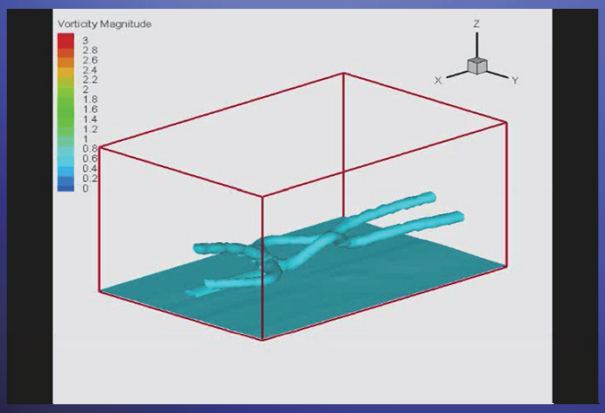
	Numerical Weather Prediction (NWP)	Computational Fluid Dynamics (CFD)
Flow scale	A few hundreds meters to several tens kilometer	***A few millimeters to several tens meters***
Application	Weather forecast	Aircraft design
Relationship with measurement data	Comparison (validation), ***ASSIMILATION***	Comparison (validation of CFD code)

Can we effectively utilize measurement data to improve the reliability of CFD simulation?

Back ground
- Toward prediction of wake turbulence -

Previous method





Iso surface (Vorticity magnitude)

- Able to retrieve wake turbulence in detail by using its lidar measurements after take off
- Difficulty in wake turbulence before the takeoff of a following aircraft, due to the large computational cost

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Objective of this research

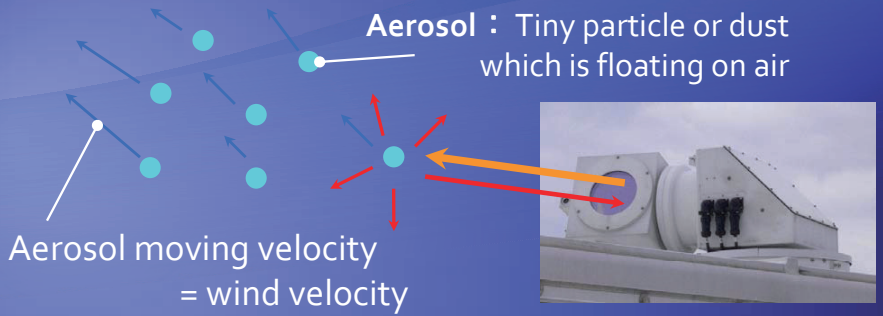
Prediction of wake turbulence under actual atmospheric conditions before the aircraft's take off

➢Approach : Data assimilation method (CFD + Experiment)
(four-dimensional variational method)

If analysis of wake turbulence can finish before the aircraft's take off, we can determine the separation time of a following aircraft's take off or landing in advance.

Approach for wake turbulence simulation

- Doppler lidar at Sendai airport -



Scanner

Doppler lidar (ENRI)

- Distance resolution
  30m (High accuracy compared to radar)
- Maximum measurement wind velocity
  more than equal to 30m/s
- Laser wave length
  less than equal to 0.5m/s
- Scanning velocity
  maximum 20m/s
- Eye-safe wavelength
- Available to measure in fine days

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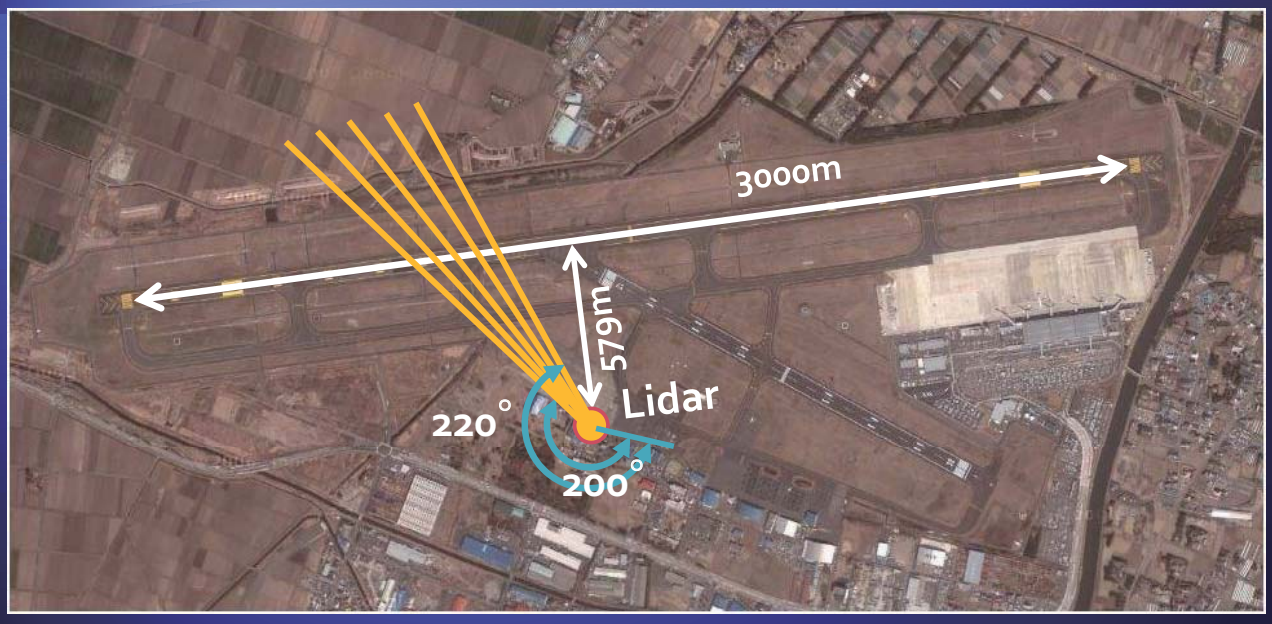
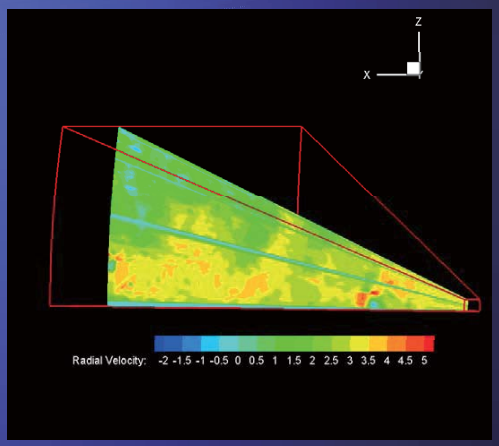
Measured velocity distribution at Sendai airport



Sendai airport

Measured velocity distribution at Sendai airport

Take off at Sendai airport



Radial velocity

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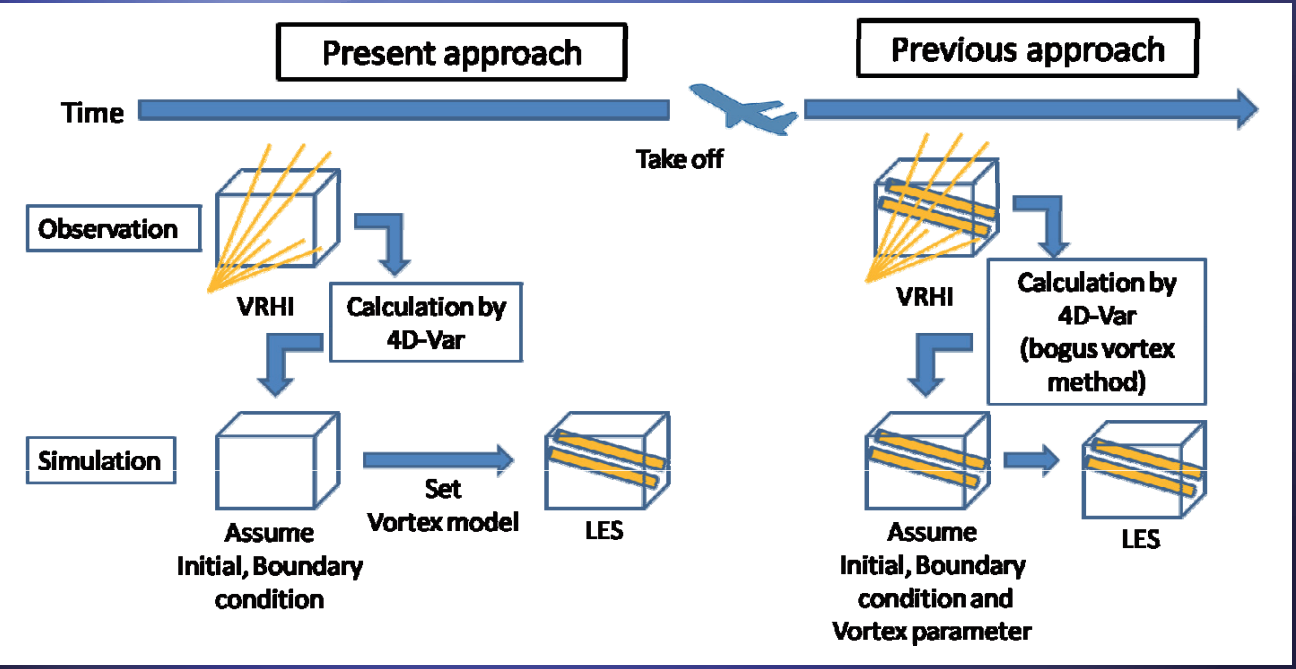
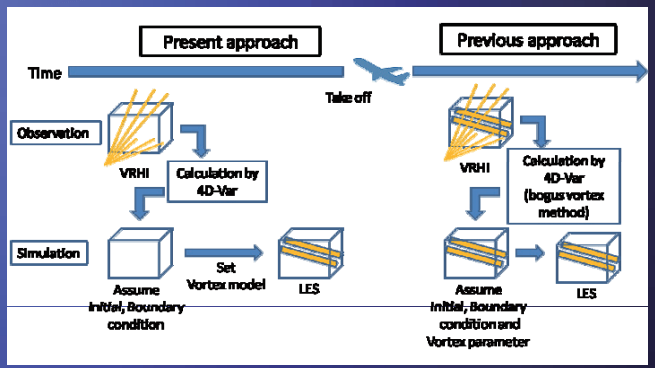
Approach for wake turbulence simulation
- Attempt to predict of wake turbulence -



Approach for wake turbulence simulation
- Attempt to predict of wake turbulence -

- Advantage of this approach
  - When the change in atmosphere is little for a long time, we can determine the separation time of a following aircraft's take off or landing based on the simulation outcome of a few hours ago.
  - We don't need high accurate wind detection system such as Doppler lidar because the target of data assimilation in this method is not vortex pair (wake turbulence) .



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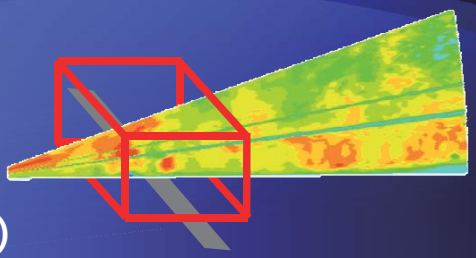
Flowchart of 4D-Var method

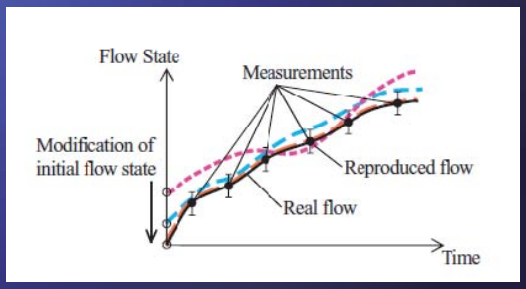


1. Simulate lidar measurement process during CFD computation (Acquiring virtual lidar measurement)

2. The difference is defined as a cost function:

3. Minimization of the cost function using adjoint equation method

→ Retrieval of unsteady flow field which agrees with time-series lidar measurements



Measurement conditions for data assimilation

- Observation date for data assimilation
  December 11 2008 16:07 (For about 90[s])
- Observation date for wake turbulence
  December 11 2008 16:15
- Target aircraft
  Boeing 777-200 (relief service)
- Weather condition
  Weather cloudy
  Wind velocity 4[m/s]*
  Wind direction SSW*
  Pressure 1007[hPa]**
  Temperature 14.5° **

Boeing 777-200

Category	Heavy
Wing span	60.9 m
Length	63.7 m

* Japan Meteorological Agency
** METAR

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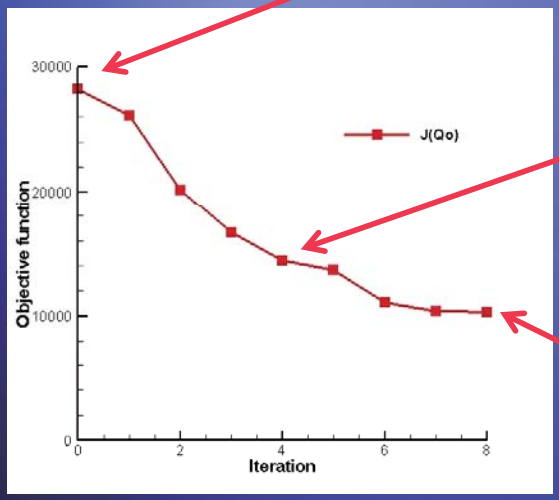
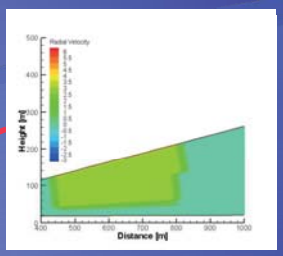
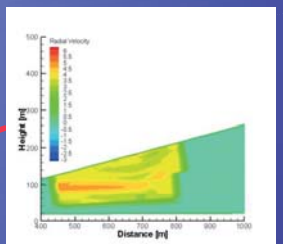
Setting of computational domain and lidar azimuth angle

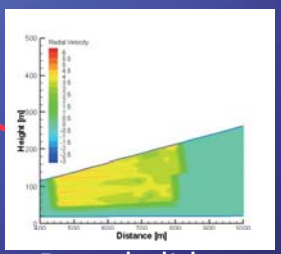
Sendai airport

Results - Minimization history of cost function -

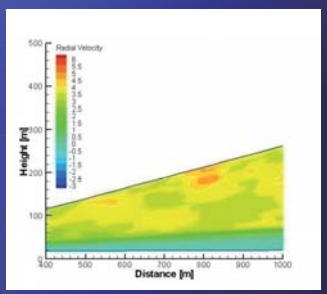








Pseudo lidar measurement (Radial velocity)



Actual lidar measurement (Radial velocity)

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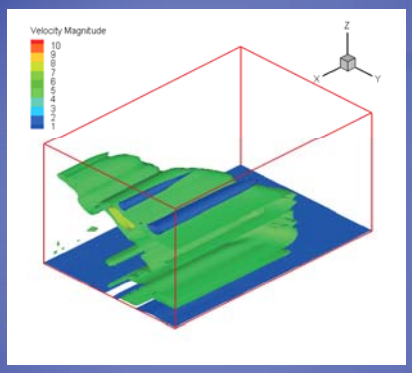
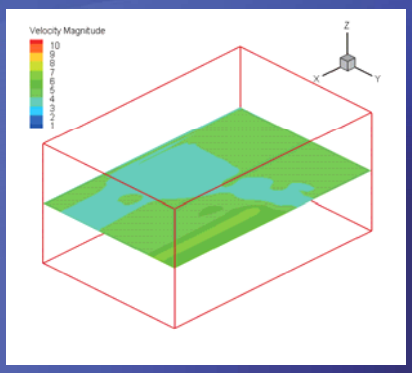
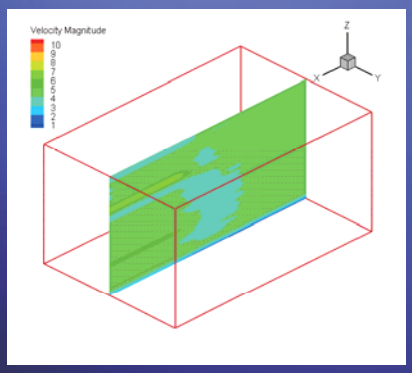
Results -Assimilated background wind field-



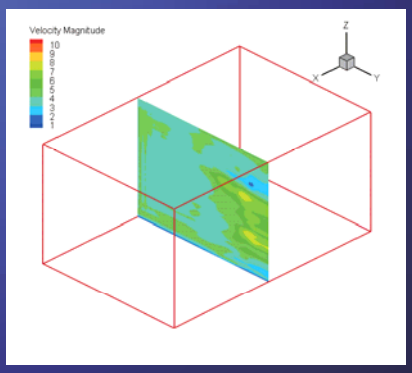
Iso surface (Velocity magnitude)



XY plane (Velocity magnitude)



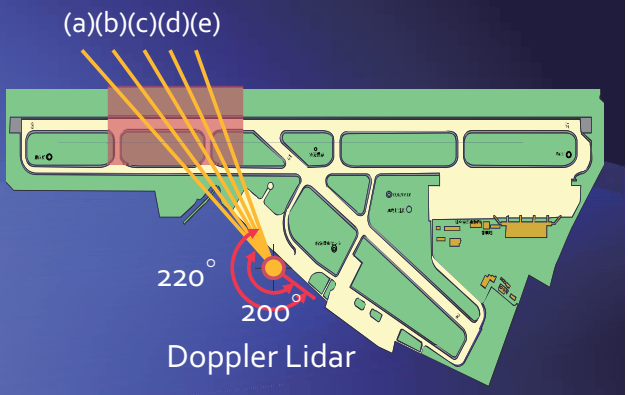
XZ plane (Velocity magnitude)



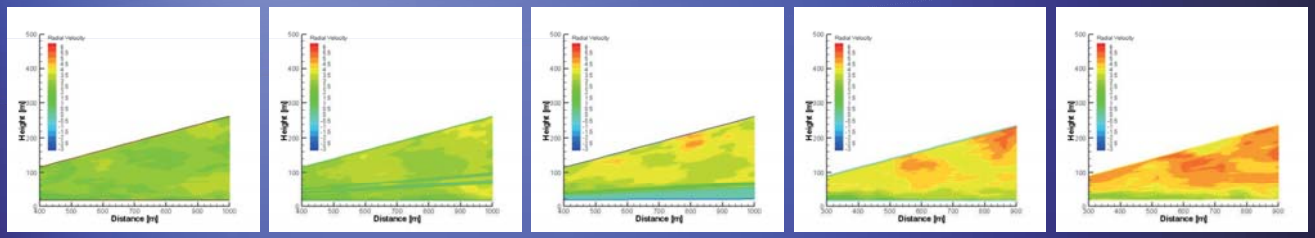
YZ plane (Velocity magnitude)

Results

-Assimilated wind field on measurement plane-

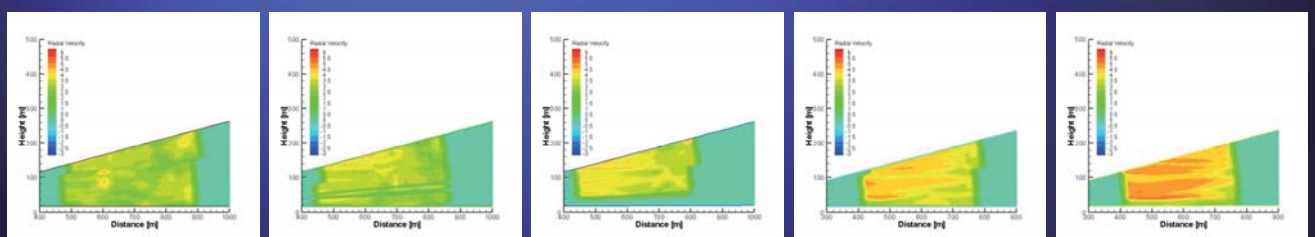


Actual



(a) 200° (b) 205° (c) 210° (d) 215° (e) 220°

Pseudo

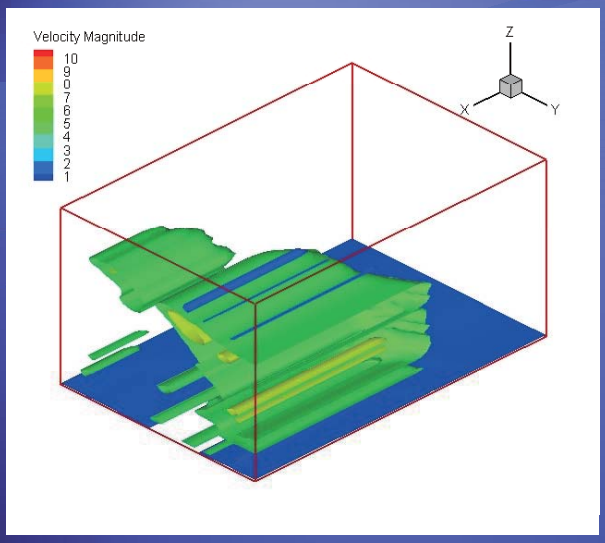


(a) 200° (b) 205° (c) 210° (d) 215° (e) 220°

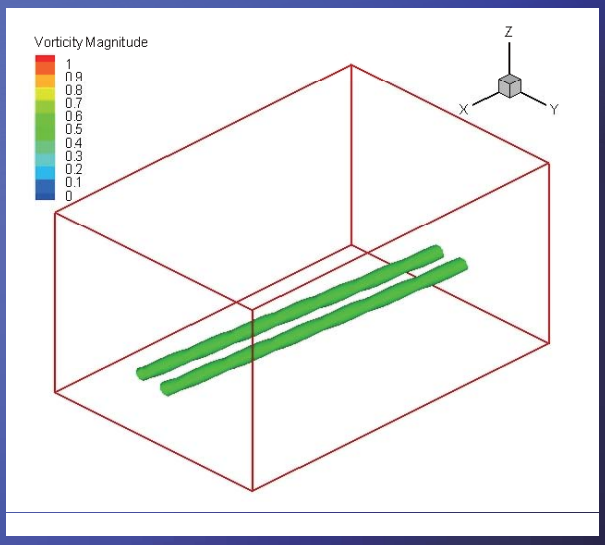
This document is provided by JAXA.

Wake turbulence simulation under actual condition

- Superposition of a vortex pair on assimilated wind field -



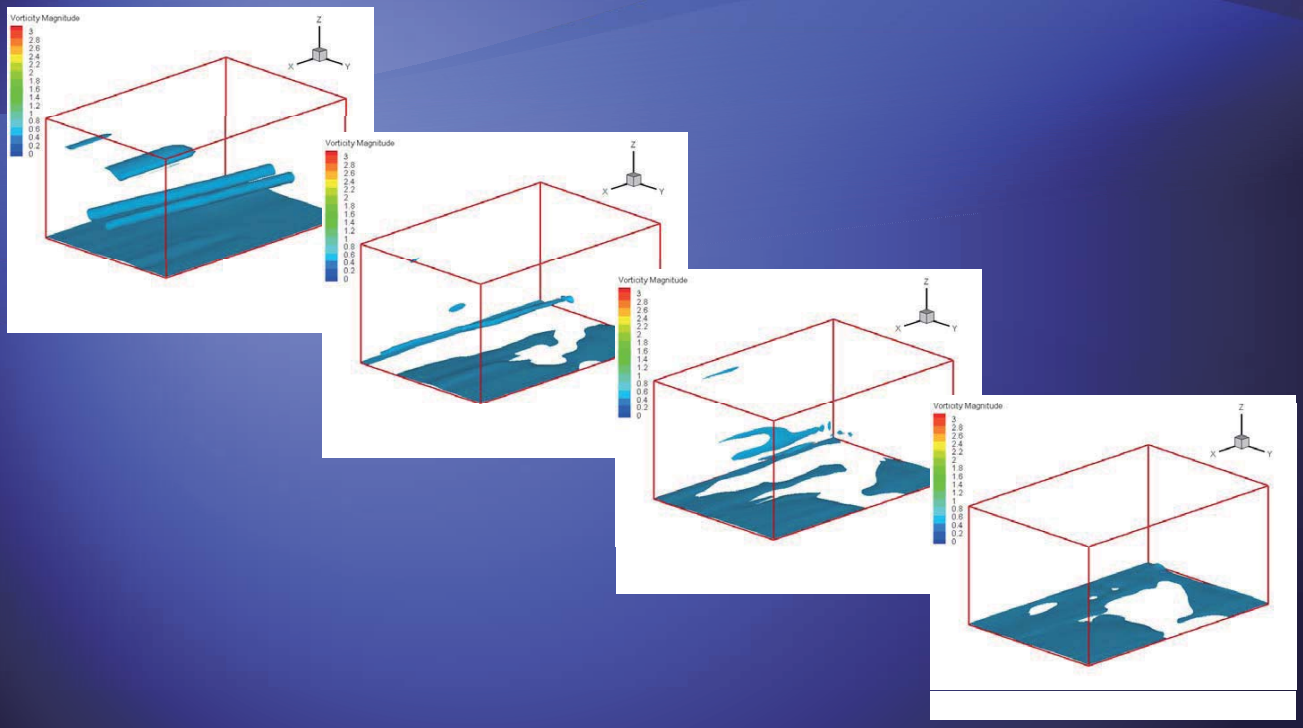
Iso surface (Velocity magnitude)



Iso surface (Vorticity magnitude)

Superimposed simulation

Results -Simulation of a vortex pair-



Iso surface (Vorticity magnitude)

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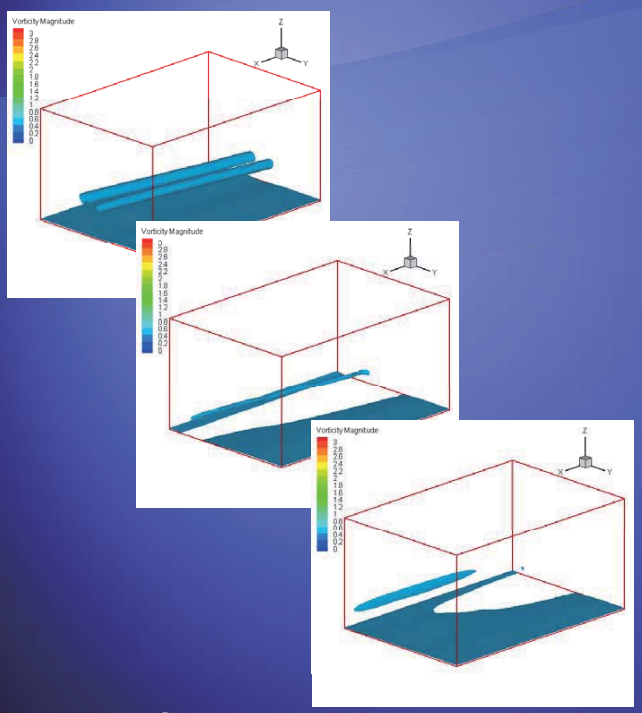
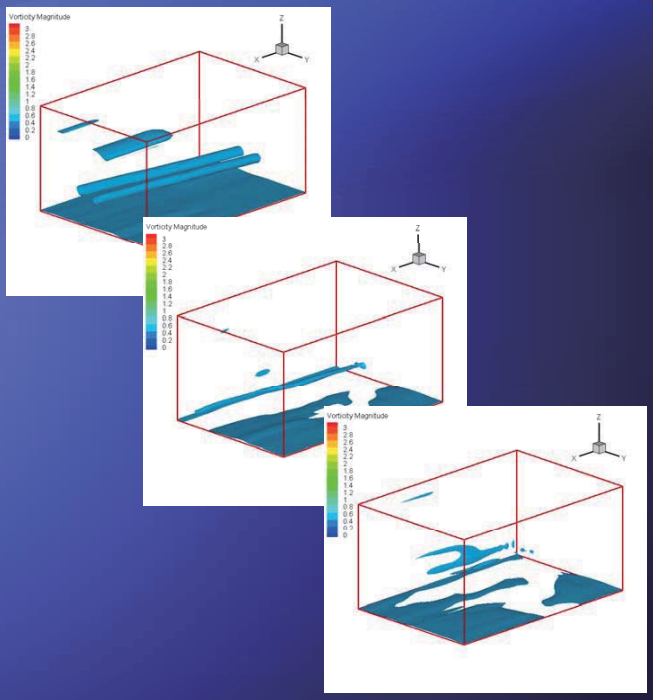
Results

-Comparison between vortices under uniform and assimilated wind field-



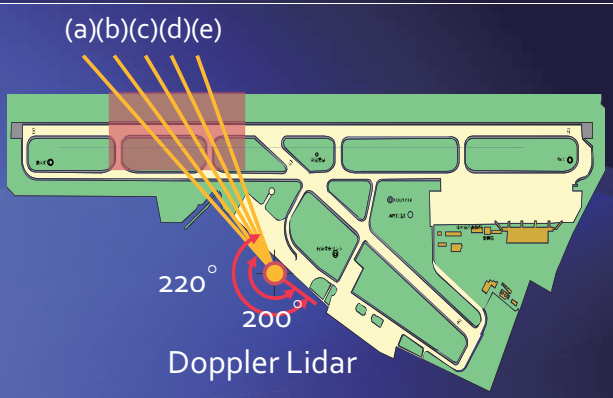
Iso surface (Vorticity magnitude)
Uniform stream condition



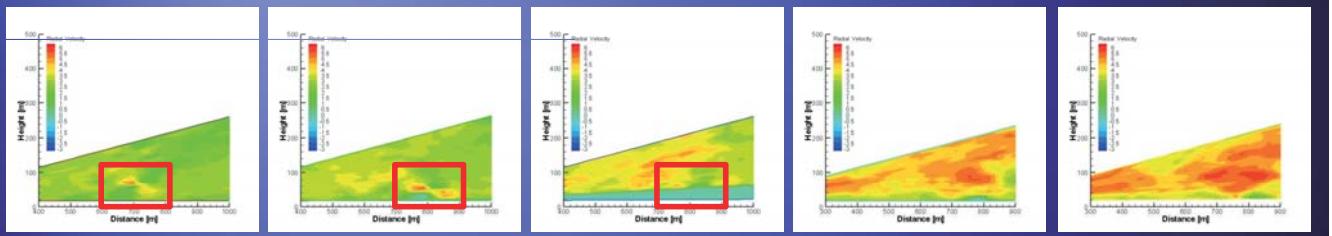
Iso surface (Vorticity magnitude)
Assimilated initial condition

Results

-Velocity distribution on measurement planes-

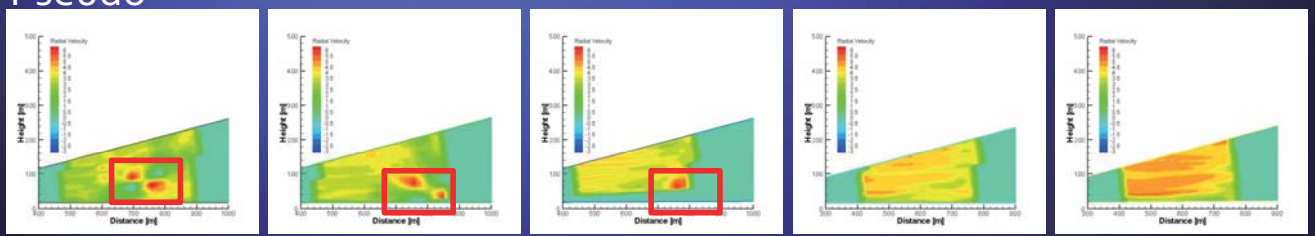


Actual



(a) 200° (b) 205° (c) 210° (d) 215° (e) 220°

Pseudo



(a) 200° (b) 205° (c) 210° (d) 215° (e) 220°

This document is provided by JAXA.

Conclusions

Wake turbulence has been simulated by using a back ground wind field prior to takeoff aiming to predict the wake turbulence in advance.

- Retrieval of a background wind field prior to takeoff was performed to predict a behavior of wake turbulence in advance.
- Advection of simulated vortex pair was similar to the actual advection of wake turbulence.
- Difference of vortex pair's decay between in uniform and assimilated wind fields showed the effect of actual conditions.

Thank you for your kind attention

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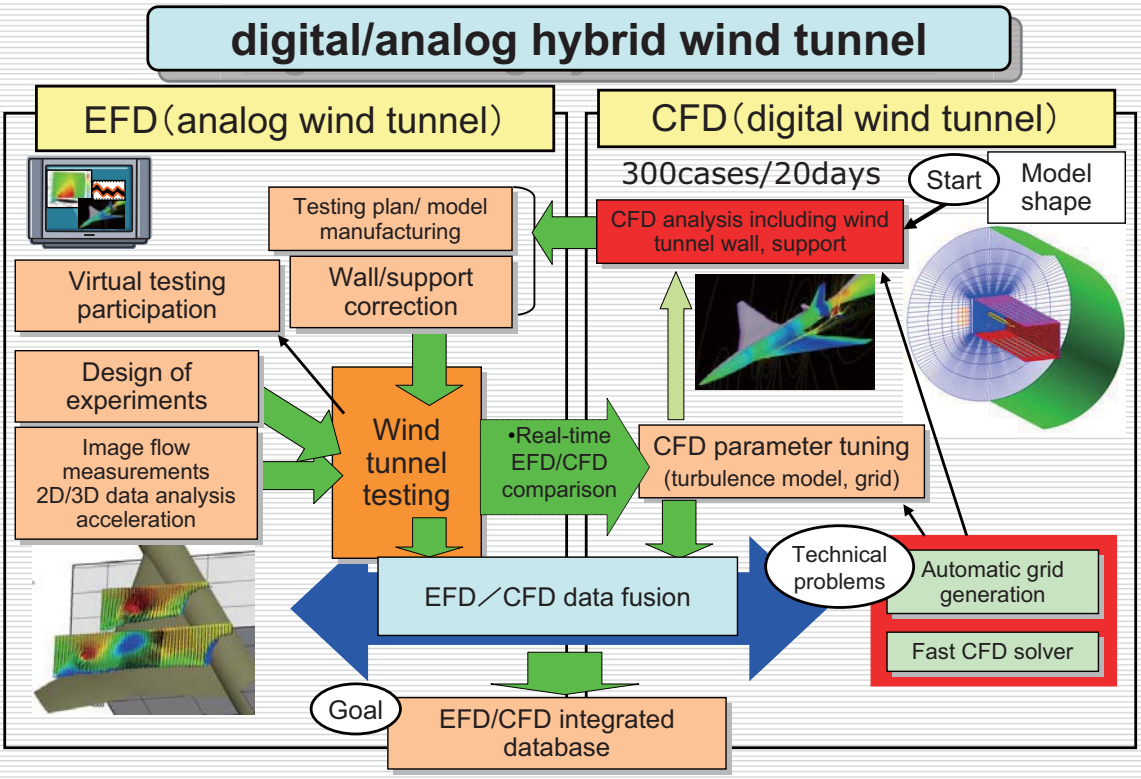
2008/02/24 Second Workshop on Integration of EFD and CFD

JAXA デジタル/アナログ・ハイブリッド風洞：デジタル風洞の開発

JAXA Digital/Analog Hybrid Wind Tunnel: Development of Digital Wind Tunnel

Atsushi Hashimoto, Keiichi Murakami and Takashi Aoyama
Numerical Analysis Group (NAG)
Japan Aerospace Exploration Agency (JAXA)

Concept of digital/analog hybrid wind tunnel



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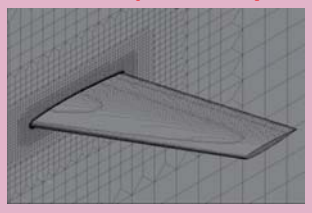
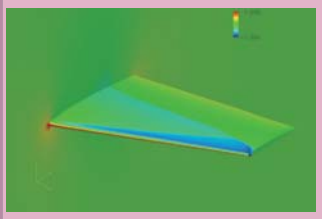
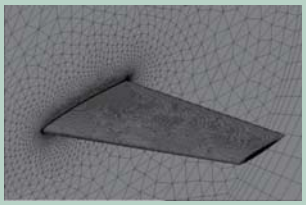
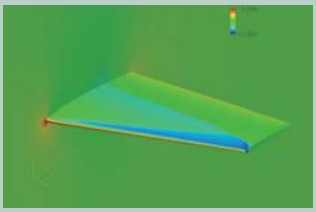
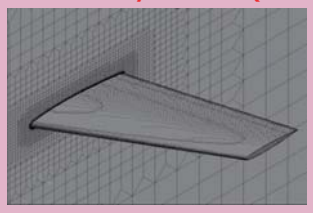
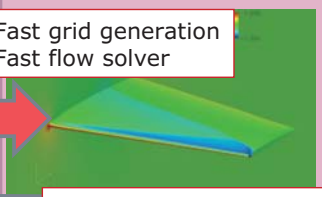
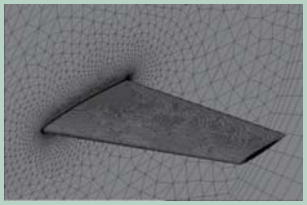
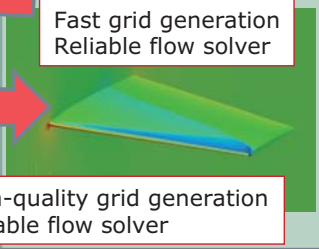
Concept of Digital Wind Tunnel

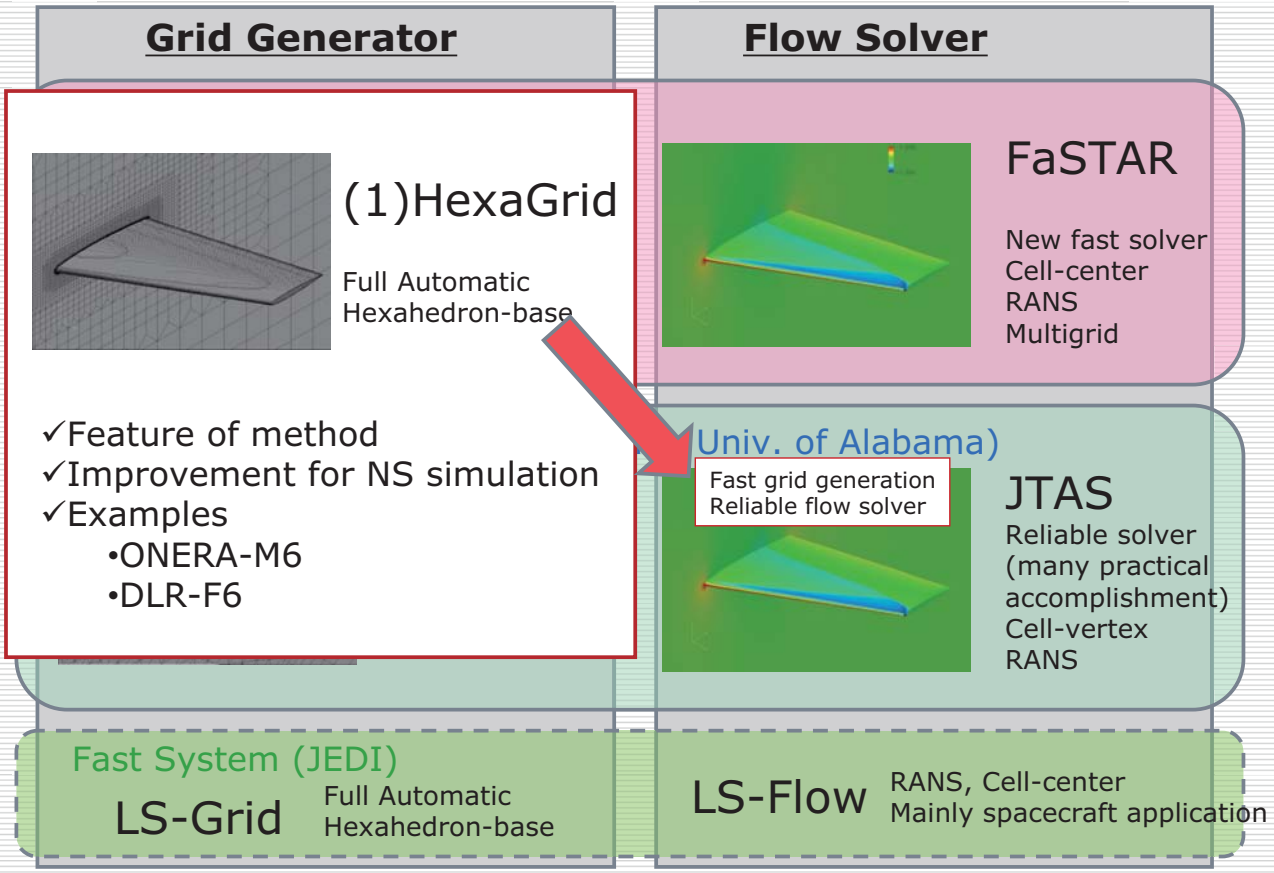
Grid Generator	Flow Solver
Fast System (NAG)	
 HexaGrid Full Automatic Hexahedron-base	 FaSTAR New fast solver Cell-center RANS Multigrid
Reliable System (APG, Tohoku Univ., Univ. of Alabama)	
 MEGG3D Semi-automatic Tetrahedron-base	 JTAS Reliable solver (many practical accomplishment) Cell-vertex RANS
Fast System (JEDI)	
LS-Grid Full Automatic Hexahedron-base	LS-Flow RANS, Cell-center spacecraft application

Concept of Digital Wind Tunnel

Grid Generator	Flow Solver
Fast System (NAG)	
 HexaGrid Full Automatic Hexahedron-base	Fast grid generation Fast flow solver  FaSTAR New fast solver Cell-center RANS ltigrid
	High-quality grid generation Fast flow solver
Reliable System (APG, Toho Univ. of Alabama)	
 MEGG3D Semi-automatic Tetrahedron-base	Fast grid generation Reliable flow solver  JTAS Reliable solver (many practical accomplishment) Cell-vertex RANS
	High-quality grid generation Reliable flow solver
Fast System (JEDI)	
LS-Grid Full Automatic Hexahedron-base	LS-Flow RANS, Cell-center Mainly spacecraft application

This document is provided by JAXA.

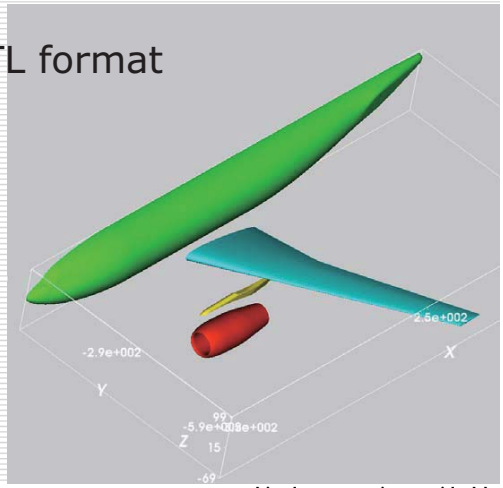
Concept of Digital Wind Tunnel



Features of HexaGrid

HexaGrid :
Automatic grid generator based on hexahedral grid

- Unstructured mesh based on Cartesian mesh
  - Handles complex geometry
  - Automatic operation (very few control parameters)
  - Fast (within minutes)
  - High quality elements (predominantly hexahedral)
- Input multi-component geometry in STL format
- Run on ordinary PC

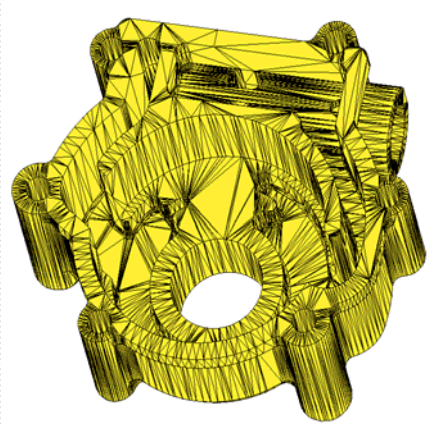


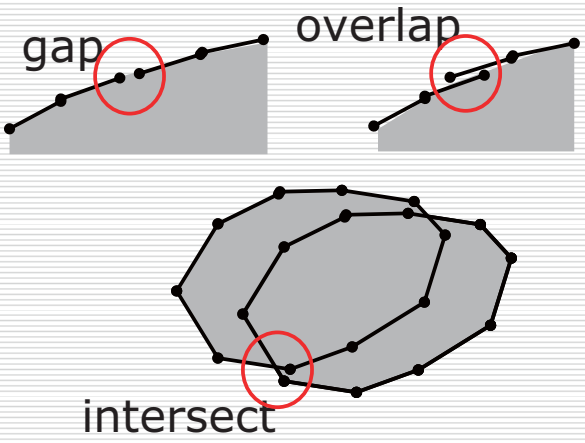
This document is provided by JAXA.

Input Data

- Triangulated surface in STL (STereo Lithography) format
  ➔ can be made by most CAD software

- Very tolerant to "dirty surface mesh"
  - Unconnected triangles ➔ non-water-tight surface is OK
  - Small gap, overlap & intersection are OK
  - Any triangle size is OK

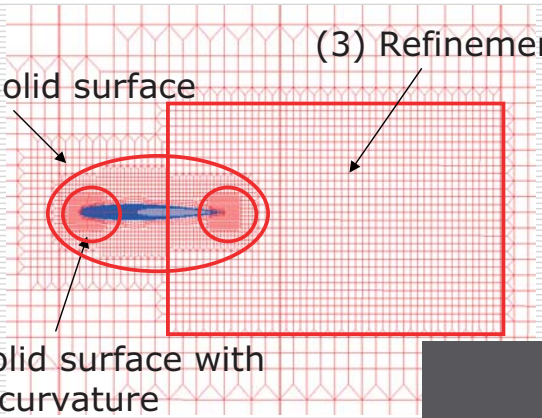




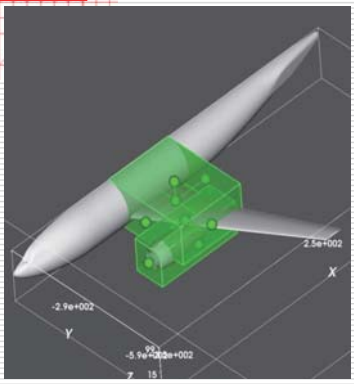
*2D illustration, the actual is 3D

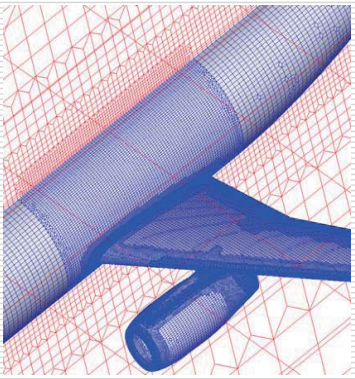
Mesh Refinement Control

- Refine the element using 3 criteria
- Each criterion has a target element size (user-defined)



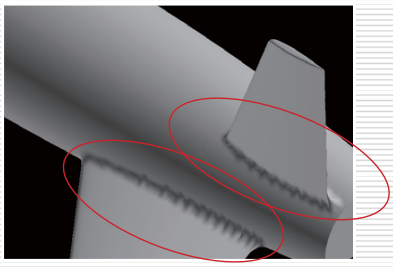
Example of Refinement box



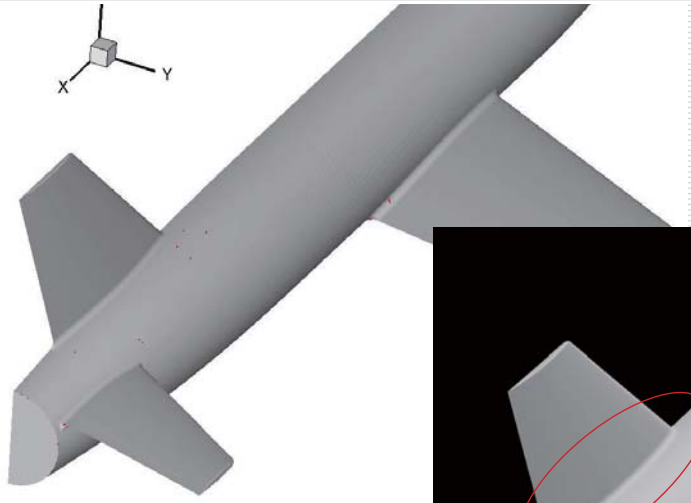


This document is provided by JAXA.

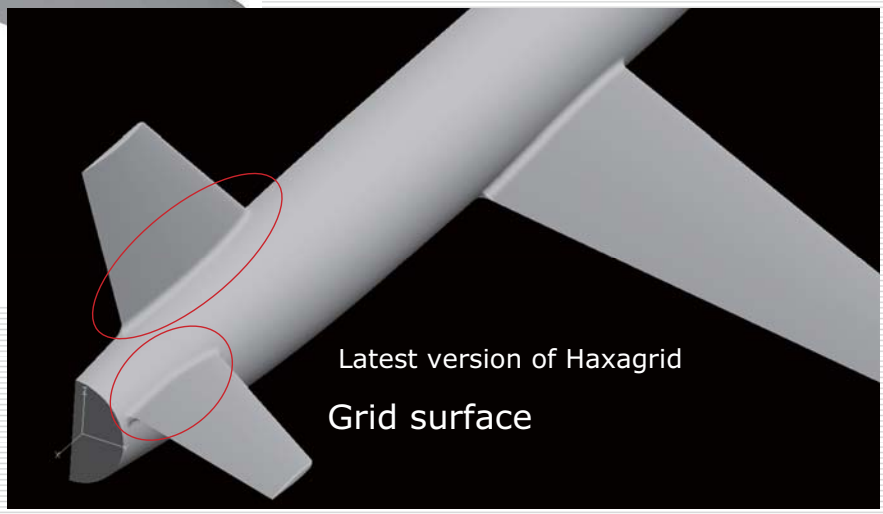
Feature capturing



Previous version of Haxagrid

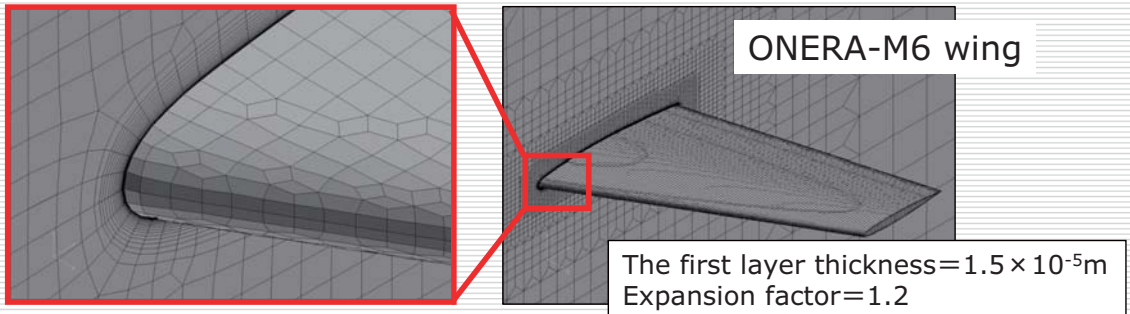


STL data

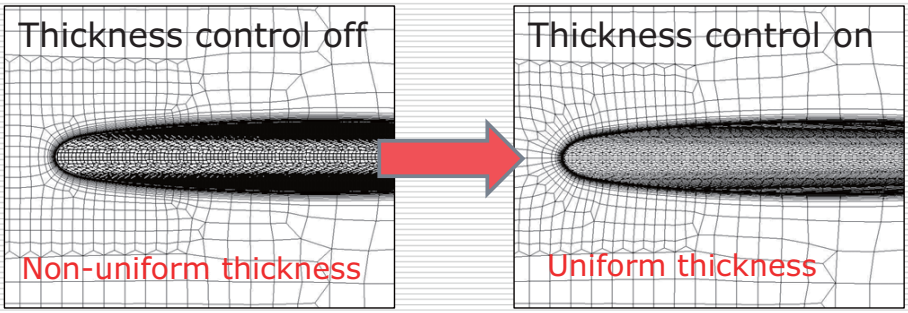


Prismatic Layer Control

HexaGrid was developed for Euler computation.
➔ Improvement of prism layer quality for RANS computation



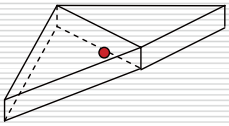
We add two control parameters;
1)Thickness of first layer and 2)expansion factor



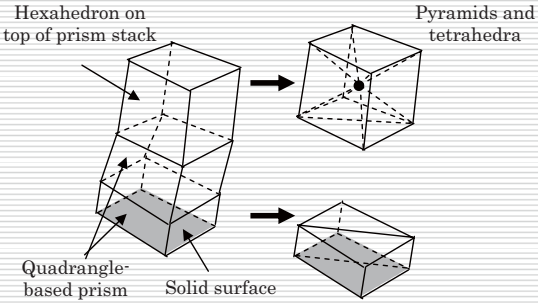
This document is provided by JAXA.

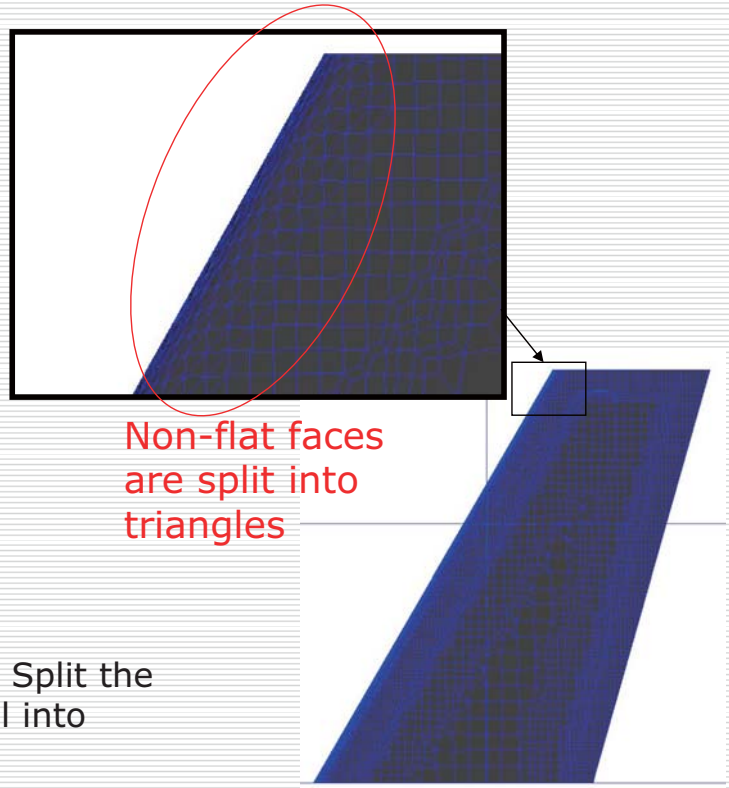
Splitting of non-flat cell

Non-flat thin hexahedral cell



Center of the cell may be outside of the cell



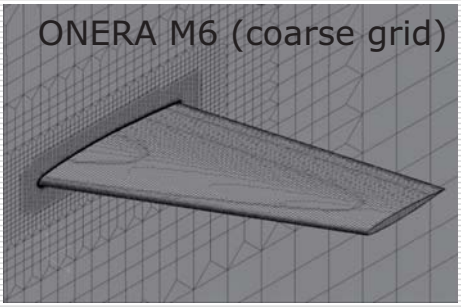


Non-flat faces are split into triangles

If rectangular face is not flat, Split the rectangle-based prismatic cell into triangle-based prismatic cell.

Grid Generation Speed

	Coarse grid	Fine grid
Cartesian level	14	15
Number of layers	30	27
Number of cells	729,173	2,232,950
Number of nodes	619,662	1,958,430
Time to generate Cartesian cells	12 sec	32 sec
Time to generate prismatic layers	19 sec	63 sec

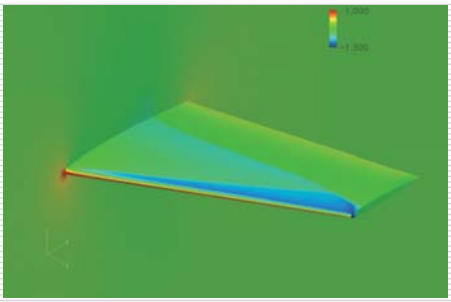


Intel Core 2 Duo T7700 2.4GHz CPU, 2 GB memory

→ **Very fast grid generation**

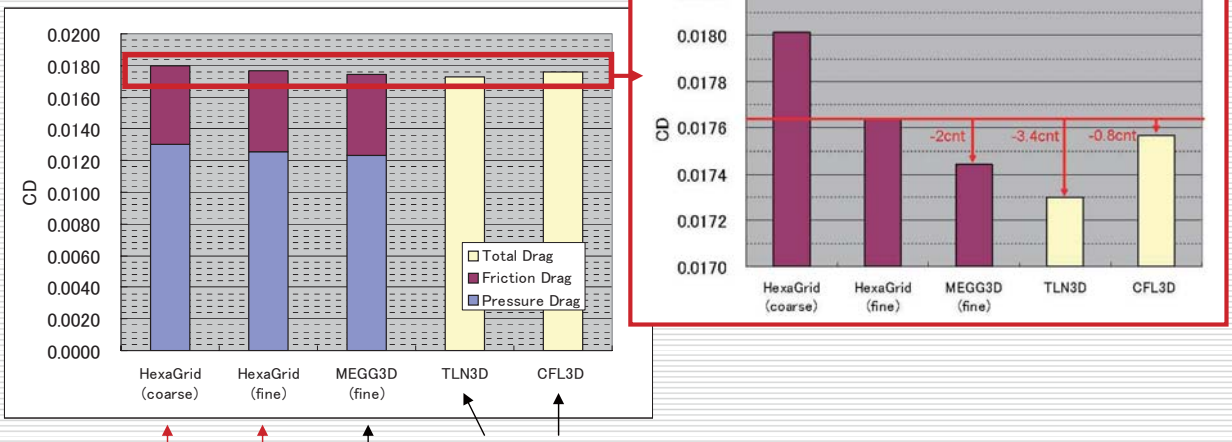
This document is provided by JAXA.

Validation (ONERA M6)



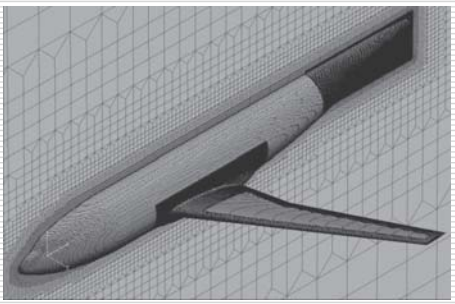
Comparison of drag coefficient with other results

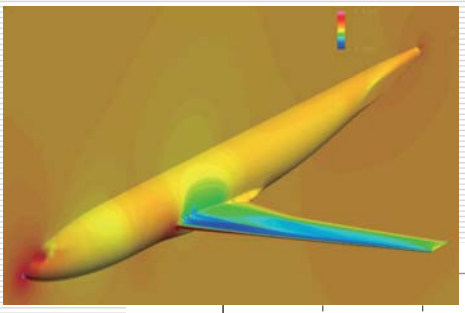
Good agreement was obtained



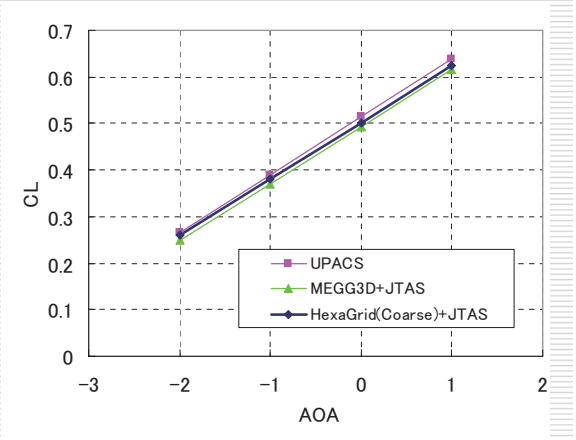
HexaGrid MEGG3D Structured grid (Bonhaus、AIAA 1990)

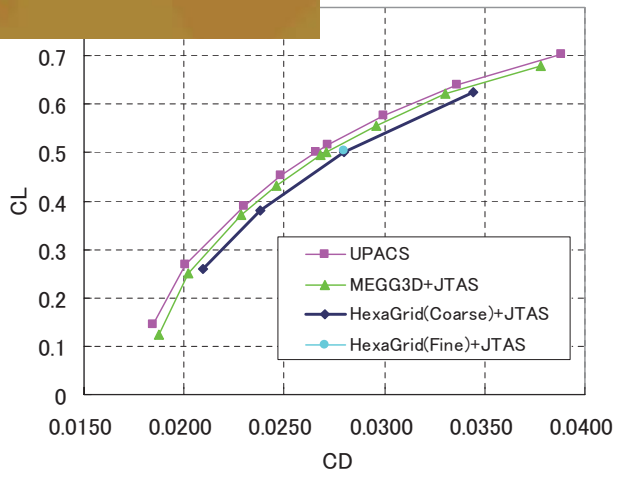
Validation (DLR-F6 FX2B)





HexaGrid agrees with other results. The difference is 10-15 counts





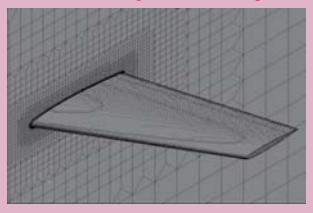
UPACS, MEGG3D+JTAS (Murayama et al., AIAA 2007-258)
Number of grid: 9.3M(UPACS), 10.0M(MEGG3D), 4.5M(HexaGrid)

This document is provided by JAXA.

Concept of Digital Wind Tunnel

Gridgen
(structured & Unstructured Grid)

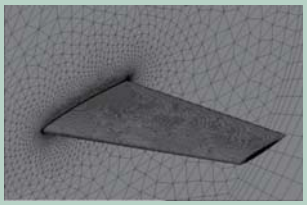
Fast System (NAG)



HexaGrid

Full Automatic
Hexahedron-base

Reliable System (APG, Toho[illegible]un



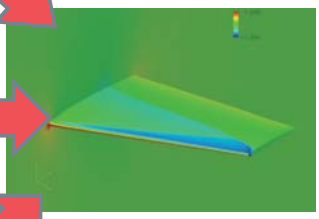
MEGG3D

Semi-automatic
Tetrahedron-base

Fast System (JEDI)

LS-Grid Full Automatic Hexahedron-base

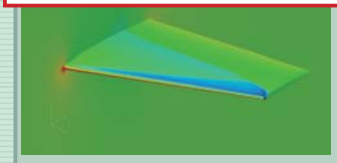
Flow Solver



(2)FaSTAR

New fast solver
Cell-center
RANS
Multigrid

✓Concept, Target
✓Configuration, Plan
✓Examples



Reliable solver
(many practical accomplishment)
Cell-vertex
RANS

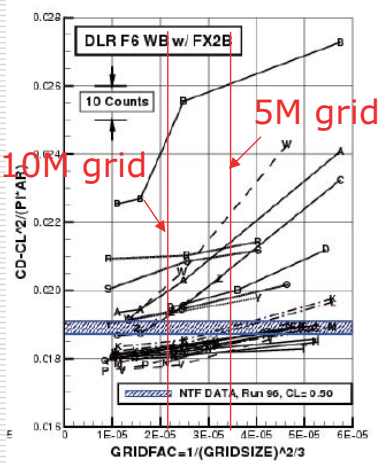
LS-Flow RANS, Cell-center
Mainly spacecraft application

Target of FaSTAR

FaSTAR (**FAST** **A**erodynamic **R**outines)
We develop a new code from scratch.

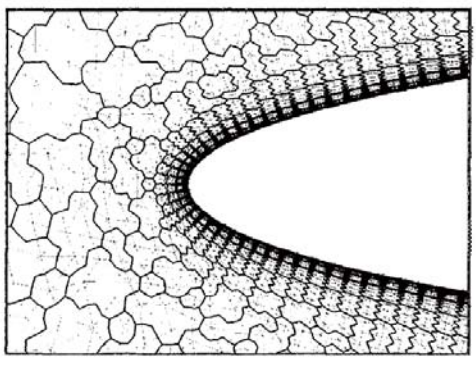
Target: 300cases/20days
(300cases =1/5 of a wind tunnel test campaign)
→1 hour/case, 100CPU, 10M Grid

≒1.5 hour, 96CPU, 15M Grid (NSU3D, Mavriplis)



Third Drag Prediction Workshop(DPW3)
Vassberg, AIAA 2008-6918

Convergence acceleration technique
(Multigrid method, GMRES) is necessary.



Agglomeration Multigrid (NSU3D)

This document is provided by JAXA.

FaSTAR configuration(1)

FaSTAR (FAST Aerodynamic Routines)

MEGG3D, HexaGrid
Gridgen(structured & unstructured grid)

↓

Pre-Process
- Data structure conversion
- Surface area, Volume
- Reordering
- Cell quality check

↓

Solver
- Flow solver (using minimum data)

↓

Post-Process
- Visualization data

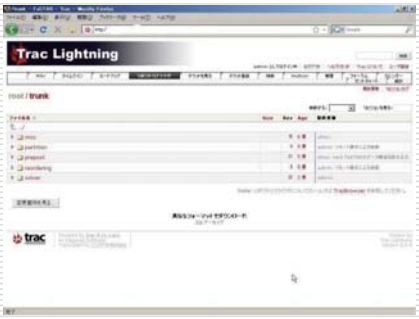
↓

Aerodynamic force
Visualization (Fieldview, Tecplot)

Separation of process
Compact design → Improvement of development efficiency and maintenance

Development tools
- ✓Subversion
- ✓Trac
- ✓Doxygen

Development based on coding rule



Trac Lightning

FaSTAR configuration(2)

Employed Schemes

Governing Equation: Euler, Thin layer/Full N-S
Discretization: Cell base
Data Structure: Face base
Reordering: Cuthill-Mackee
Flux: Roe, HLLE, AUSM+
Turbulence model: SA, SST
Convergence acceleration: Agglomeration Multigrid, Krylov method (GMRES)
Grid Partition: Zoltan (METIS)
Parallel library: MPI

Survey of well-known CFD code

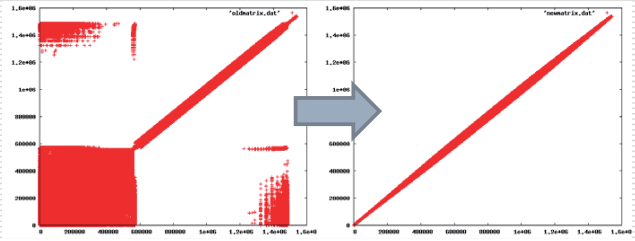
JTAS
NSU3D
BCFD
EDGE
UG3
USM3D
FUN3D

FaSTAR data structure

Cell
↑ face2cell
Face
BD Face

Almost all loops are written in face loop.
- ➢Gradient
- ➢Flux
- ➢LU-SGS sweep

Cuthill Mackee reordering
=Hyperplane reordering
(speed up by 20%)



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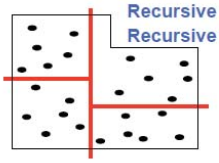
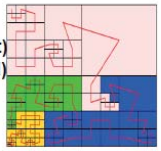
Domain Partition

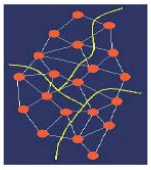
Zoltan toolkit includes the following methods



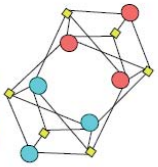
Recursive Coordinate Bisection (Berger, Bokhari)
Recursive Inertial Bisection (Taylor, Nour-Omid)



Space Filling Curves (Peano, Hilbert)
Refinement-tree Partitioning (Mitchell)



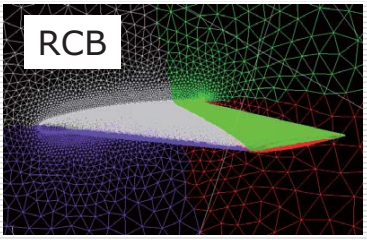
Graph Partitioning
ParMETIS (Karypis, Schloegel, Kumar)
Jostle (Walshaw)

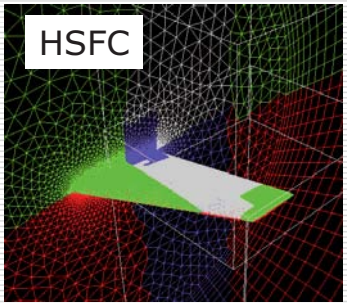


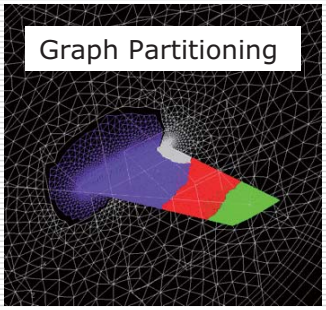
Hypergraph Partitioning & Repartitioning
(Catalyurek, Aykanat, Boman, Devine, Heaphy, Karypis, Bisseling)
PaToH (Catalyurek)

(Zoltan tutorial)

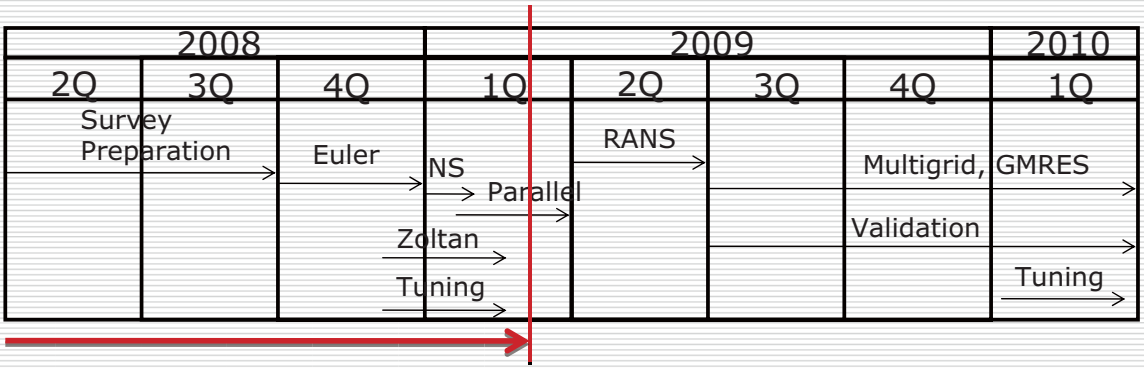
Examples of partitioned grids



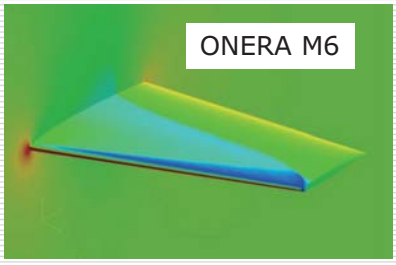


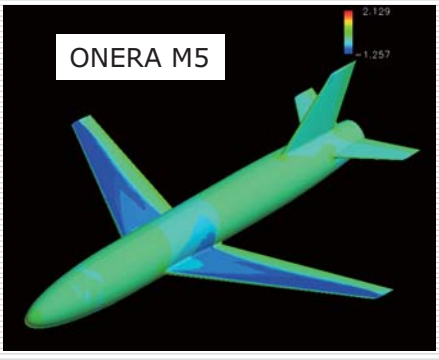


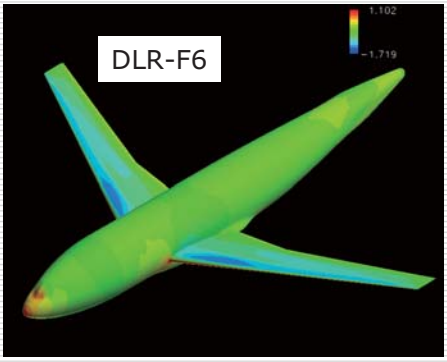
Plan



Preliminary results using FaSTAR(Euler)
FaSTAR achieves 1.1GFlops on 1CPU of JSS (11% of theoretical peak performance)





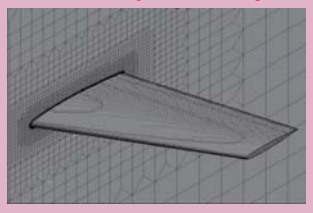


This document is provided by JAXA.

Concept of Digital Wind Tunnel

Grid Generator

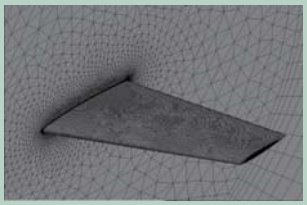
Fast System (NAG)



HexaGrid

Full Automatic
Hexahedron-base

Reliable System (APG, Tohoku U[illegible] Univ. of Alabama)



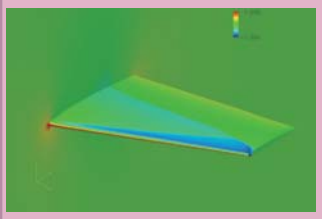
MEGG3D

Semi-automatic
Tetrahedron-base

Fast System (JEDI)

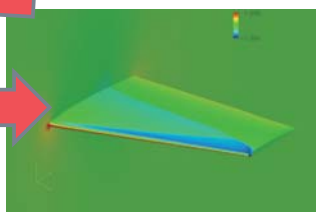
LS-Grid Full Automatic
Hexahedron-base

Flow Solver



FaSTAR

New fast solver
Cell-center
RANS
Multigrid



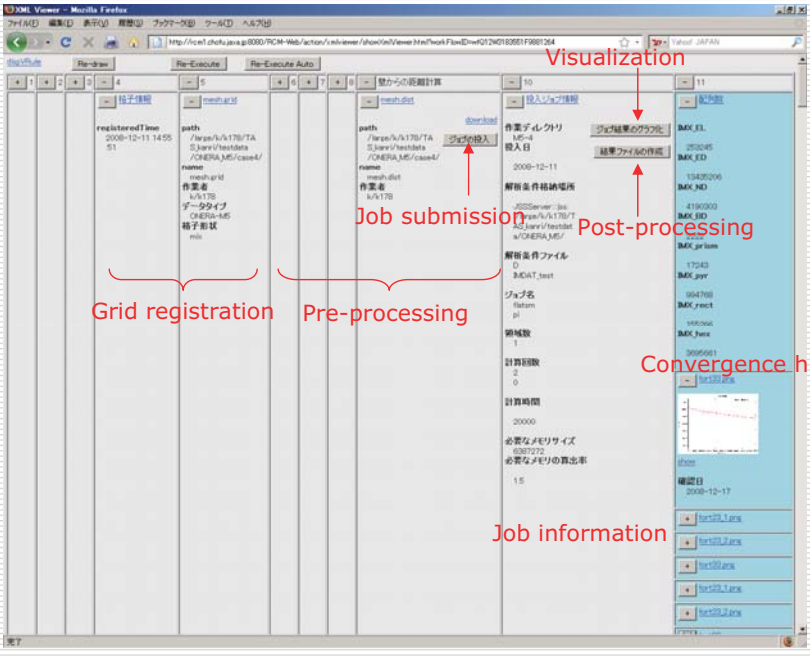
(3)JTAS

Reliable solver
(many practical accomplishment)
Cell-vertex
RANS

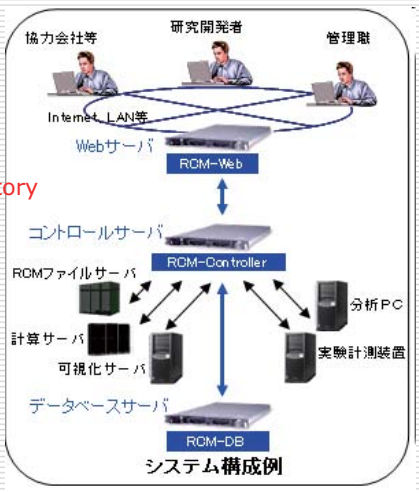
✓Installation of RCM portal
✓Whole wind tunnel simulation
(Porous wall modeling)

RCM portal system

HexaGrid+JTAS workflow system



RCM(**R**&D **C**hain **M**anagement) is a middleware integrating web server, control server, and database server.



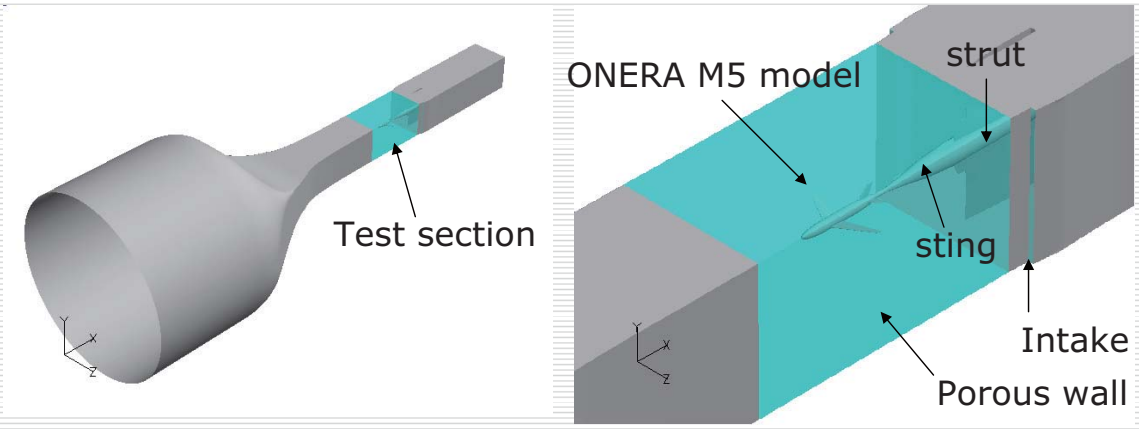
http://www.i4s.co.jp/rcm/rcmabs.html

✓User can make registration of grid and result data.
✓User can search the data using the database.
✓User can submit and monitor jobs from the web.
✓User can visualize the result from the web.

Quatre-i science

This document is provided by JAXA.

Transonic wind tunnel simulation

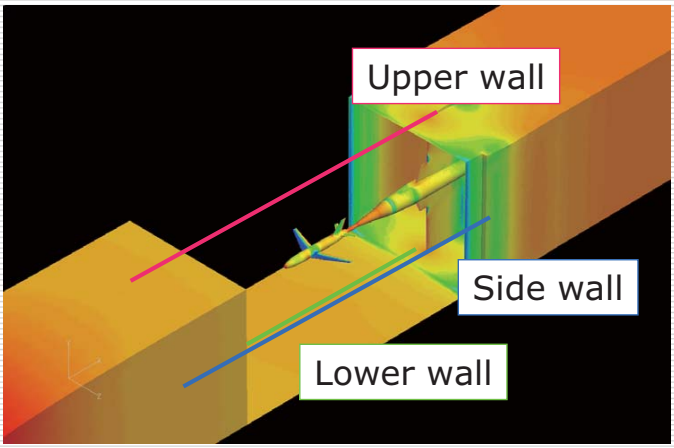


Experimental conditions: M=0.84, AoA=0deg
Re=1.67x10^6 (Re is based on MAC)

Computational conditions
inflow conditions: $P_0/P=1.58$, $T_0/T=1.14$
Outflow condition: $P_{out}/P=1.05\sim1.10(?)$
We have to adjust the outflow pressure to make M=0.84 flow at the test section.

1. Solid wall computation
2. Porous wall computation (modified Harloff model)

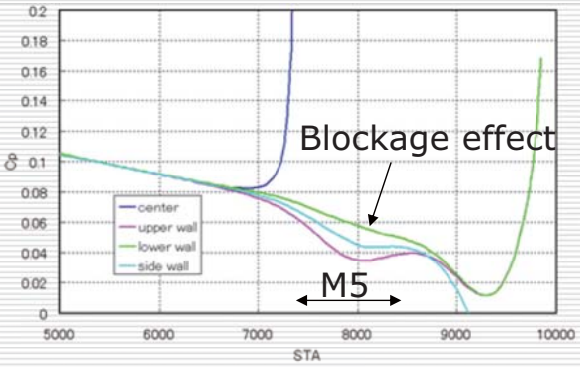
Transonic wind tunnel simulation



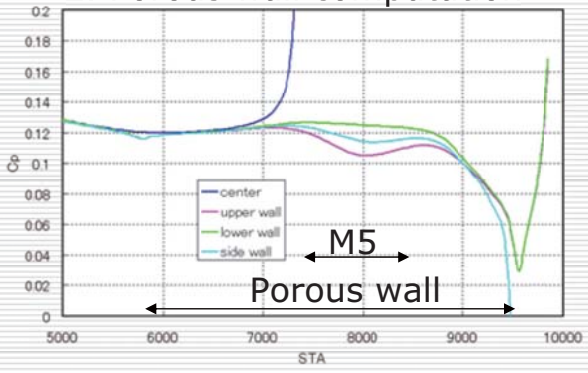
Porous wall effect can be reproduced using the Harloff model.

Streamwise pressure distribution becomes flat.

1. Solid wall computation

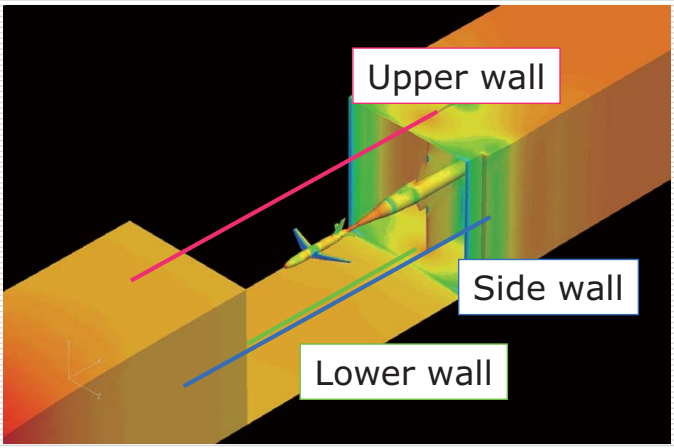


2. Porous wall computation



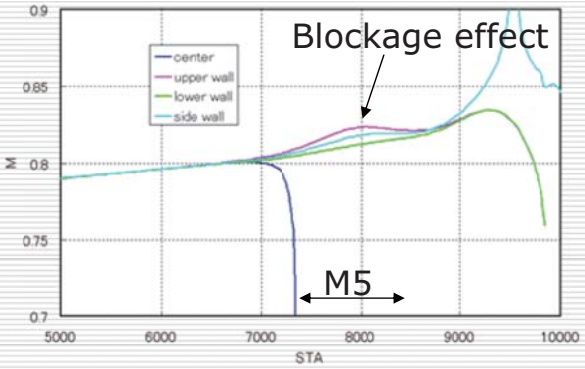
This document is provided by JAXA.

Transonic wind tunnel simulation

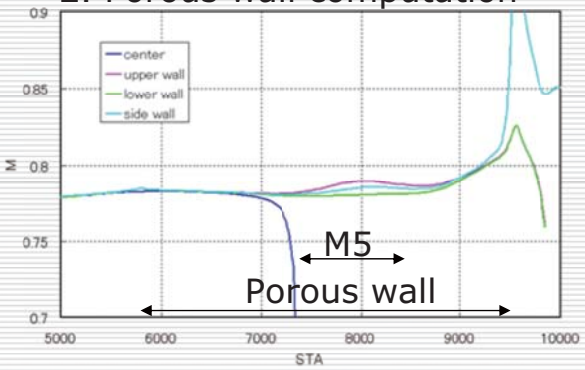


Mach number computed with isentropic relation

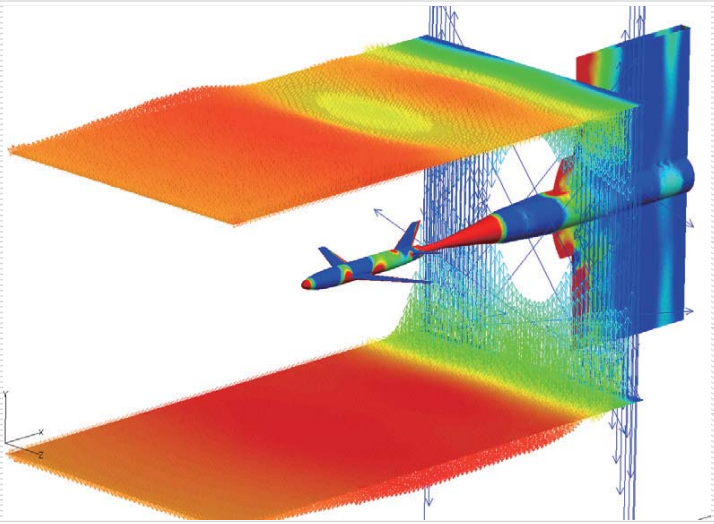
1. Solid wall computation



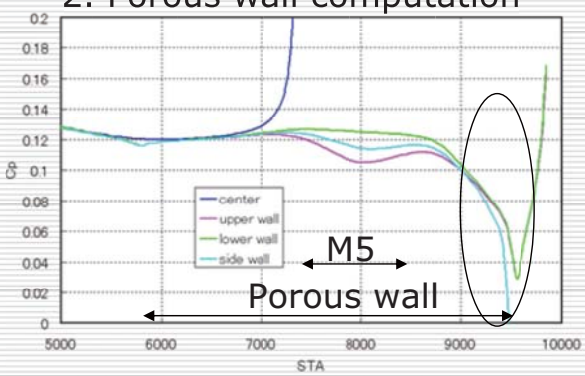
2. Porous wall computation



Transonic wind tunnel simulation



2. Porous wall computation



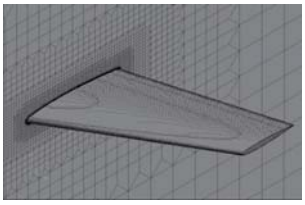
Velocity through the porous wall.
Inflow velocity is faster at the end of porous wall.

This inflow may interfere the downwash from the model.

This document is provided by JAXA.

Concept of Digital Wind Tunnel

Grid Generator



(1)HexaGrid

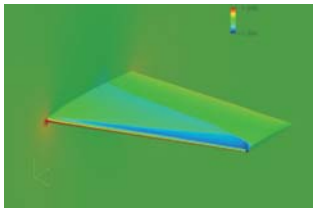
Full Automatic
Hexahedron-base

✓Feature of method
✓Improvement for NS simulation
✓Examples
- •ONERA-M6
- •DLR-F6

Fast System (JEDI)

LS-Grid

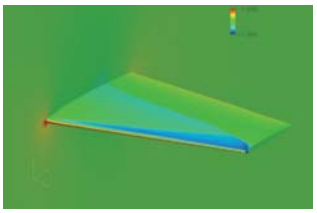
Full Automatic
Hexahedron-base



(2)FaSTAR

New fast solver
Cell-center
RANS
Multigrid

✓Concept, Target
✓Configuration, Plan
✓Examples



(3)JTAS

Reliable solver
(many practical accomplishment)
Cell-vertex
RANS

✓Installation of RCM portal
✓Whole wind tunnel simulation
(Porous wall modeling)

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JAXAデジタル/アナログ・ハイブリッド風洞：アナログ風洞の処理高速化

JAXA Digital/Analog Hybrid Wind Tunnel: Speed-Up Technique of Analog Wind Tunnel

2009(H21)年2月24日
宇宙航空研究開発機構　研究開発本部
藤田直行
Naoyuki FUJITA(JAXA)

Agenda

- What is PIV?
- Motivation of Speed-Up PIV
- Some candidates for Accelerator
- Speed-Up Evaluation using Cell/B.E.
- Future Work on Speed-Up PIV
- Conclusion

※Many Slides are in Japanese

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空間速度場計測

- 航空宇宙機開発及び流体研究における空間速度場計測の必要性
  - 機体周りの流れ場の全体像及び細部の把握
  - 乱流・剥離等の基礎流体現象解明のための基礎データ

- 計測手法

(a) 点計測　熱線風速計
5孔(or 7孔)ピトー管(平均速度場のみ)
LDV (Laser Doppler Velocimetry)

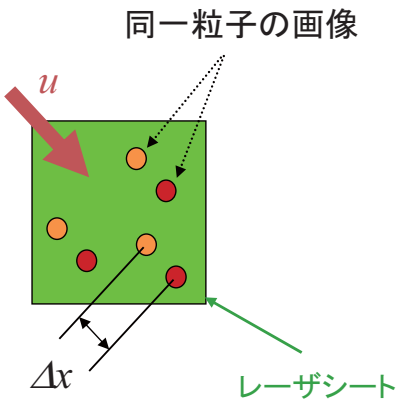
(b) 面計測　PTV (Particle Tracking Velocimetry)
PIV (Particle Image Velocimetry; 粒子画像流速測定法)
DGV (Doppler Global Velocimetry)

PIVの測定原理

レーザ光のシード粒子への
2回(●●)の照射

$$u(x,t) = \frac{\Delta x(x,t)}{\Delta t}$$

流速 = 粒子移動距離 / 時間間隔



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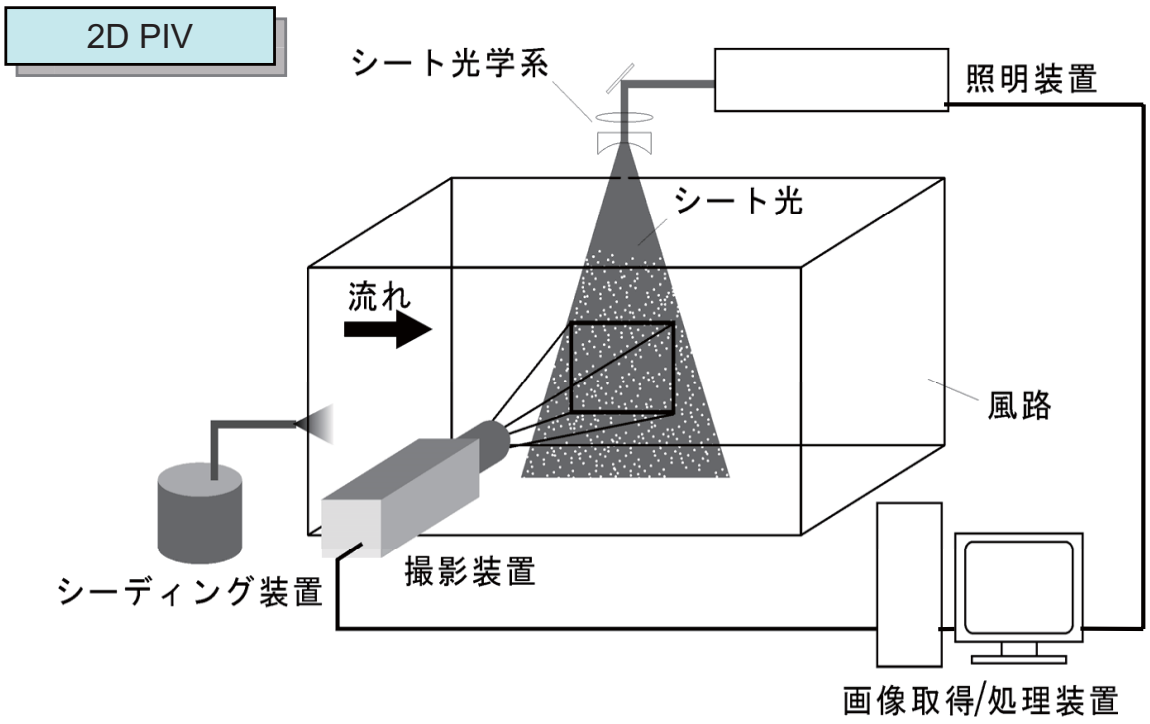
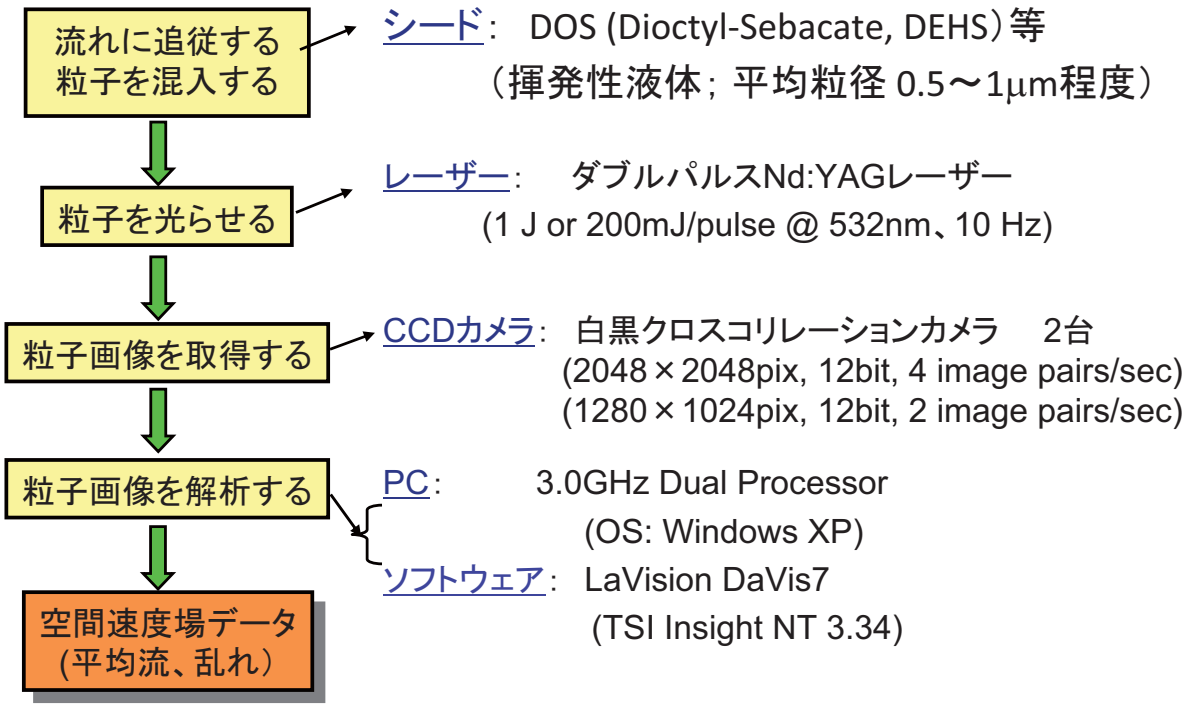
PIVシステムの基本構成



PIV計測手順とシステム構成

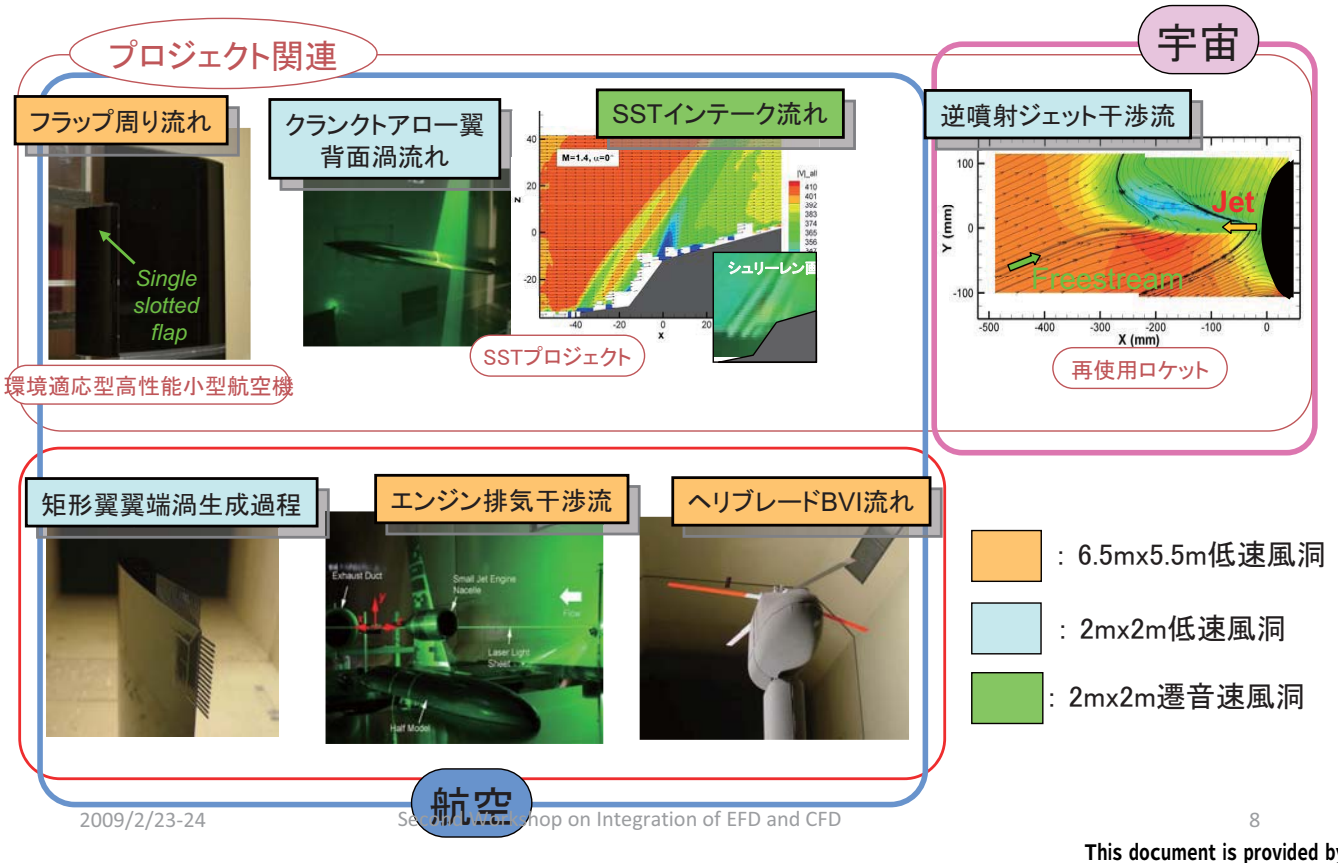


This document is provided by JAXA.

PIVの利点・欠点

- 利点
  - 非接触計測
  - 平面内の瞬時速度場が計測可能(面計測のメリット)
    - → *平均流だけでなく乱れに関する情報も入手*
    - → *点計測(熱線、ピトー管)に比べ計測時間：短*
- 欠点
  - データ取得レート：低（時系列処理には不向き）
  - 空間分解能：相対的に低
  - シード粒子を気流に混入する必要
  - セッティング、キャリブレーション、光学系調整が煩雑

JAXAにおけるPIV計測例



This document is provided by JAXA.

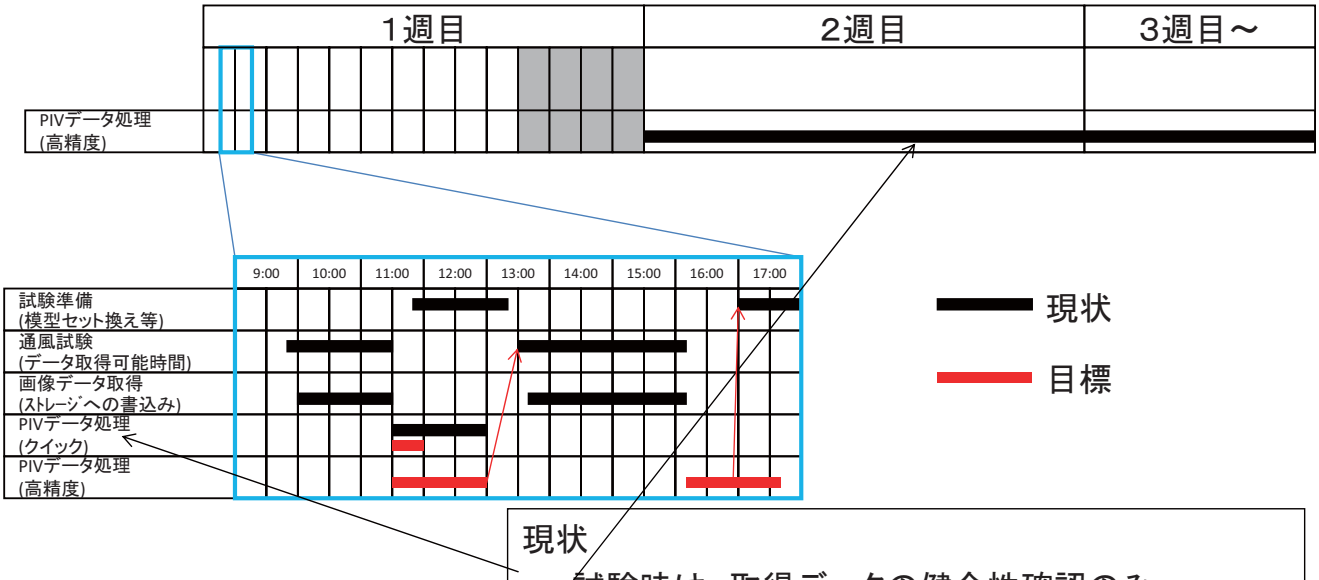
Motivation of Speed-Up PIV

既存ステレオPIVシステム
- 商用PIVソフトウェア(LaVision社DaVis Ver.7.2)
- ステレオPIV処理(PIVカメラ2台；2k×2k画素)
- PIV処理パラメータ
  - 相関窓サイズ：32×32画素、オーバーラップ：50%、再帰処理：2回
- 1,000セットの処理に要する時間(Intel Core2Quad 2.4GHz)
  - 1CPU：18.8時間、8CPU：2.7時間

現状のPIV処理手順
- 試験期間中：クイック結果のみ(10～50セットのみで簡易計算)
- データのばらつき大、流れ場の詳細評価は困難⇒取得データの健全性確認のみ
- 試験終了後：正式なPIV処理、処理終了は2～4週間後

問題点
- 試験中、CFD結果等との詳細比較の評価が困難
- 計測結果を反映した追加計測が困難

Motivation of Speed-Up PIV(Cont.)



現状
- 試験時は、取得データの健全性確認のみ
- 正式なPIV処理の終了は2～4週間後

問題点
- 試験中、CFD結果等との詳細比較の評価が困難
- 計測結果を反映した追加計測が困難

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高速化の対象とするPIVの処理概要

表1 評価対象のPIV処理条件

項目	サイズ
フレームサイズ	2000×2000[pixel]
窓A(検査領域)	32×32[pixel]
検査領域の重複率	50%オーバーラップ
探査領域	17×17(−8≦x≦8/−8≦y≦8)[pixel]
窓B(候補領域)	48×48[pixel]
1pixelのデータサイズ	16,384[諧調](14bit−モノクロ)

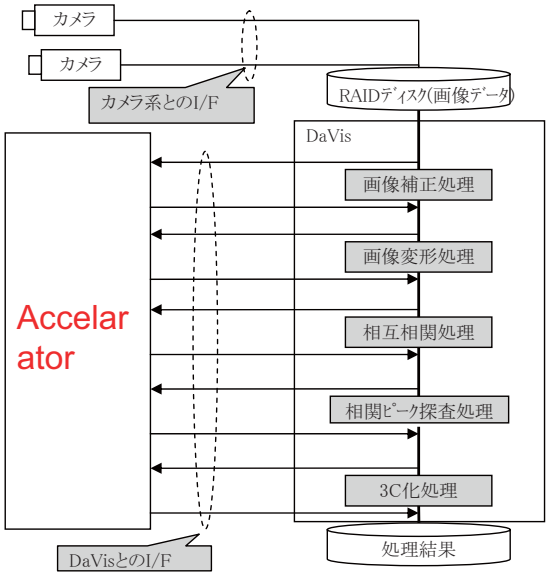
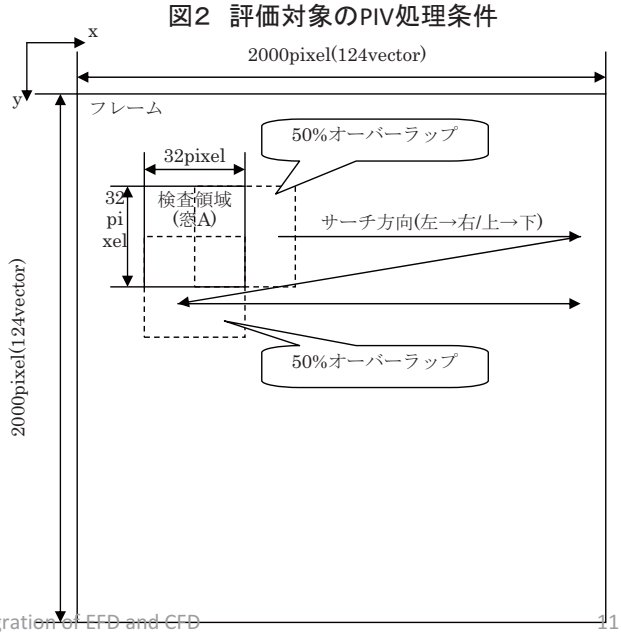


図1 PIV処理要素概要

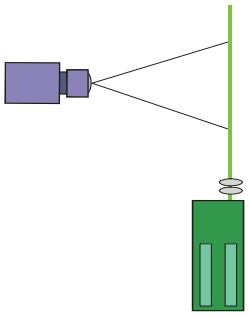
図2 評価対象のPIV処理条件



2D PIVと3D (Stereo) PIVの比較

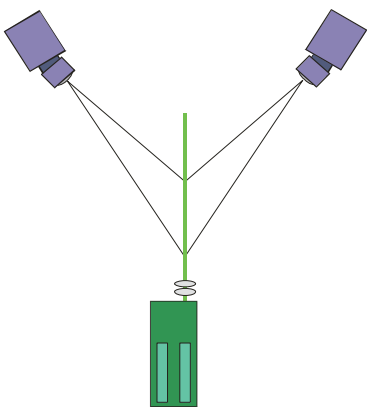
a) 2D

- カメラ 1台
- 速度 2成分 *u*, *v* (レーザーシート面内)
- 散乱光弱い(レーザーシートに垂直)



b) 3D (Stereo)

- カメラ 2台
- 速度 3成分 *u*, *v*, *w*
- 散乱光強い(前方散乱の使用)
- カメラ設置位置の自由度高い
- 画角キャリブレーションがやや煩雑



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高速化の対象とするPIVの処理概要

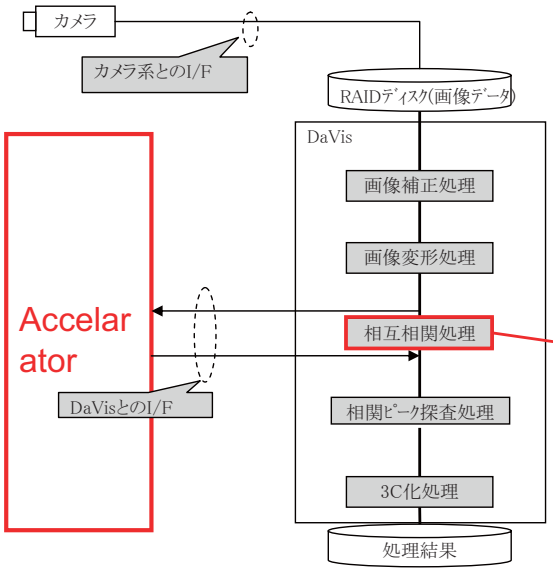

表　2D PIVにおける各処理の時間

PIV処理項目	処理時間 [ms]	アクセラレータを適用する場合の処理の複雑さ
画像補正処理	33.2	単純
画像変形処理	(2Dのため無し)	複雑
相互相関処理	10619.5	単純
相関ﾋﾟｰｸ探査処理	99.1	単純
3C化処理	(2Dのため無し)	複雑

図　PIV処理要素概要

Some candidates for Accelerator

Cell/B.E.

GPGPU

Study Items
- Speed-Up ability
- Price
- Stable Supply
- Operation Cost
- User Environment

FPGA

2009年9月14-16日
岩手大学

日本機械学会年次大会
計算力学部門特別企画
先端技術フォーラム
「計算力学の新たな潮流
—GPGPU, FPGA, CELLコンピューティング—」

PC Cluster

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Speed-Up Evaluation using Cell/B.E.(1/8)

表 1 ホストマシン環境

分類	名称	特記事項
アプリケーション	DaVis 7.2	開発元は LaVision
OS	Windows XP Professional Version2002 SP2	英語版
CPU	Dual-Core-AMD Opteron Processor 2220 2.8GHz	
メモリ	3.25GB	

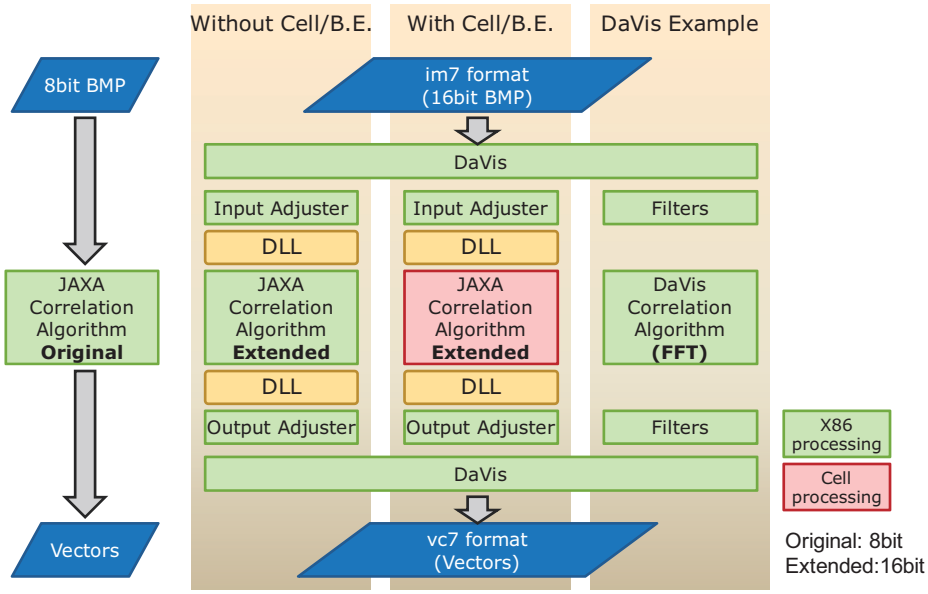
表 2 Cell/B.E. アクセラレータ GigaAccel180 環境

分類	名称	特記事項
OS	Fedora 7	
CPU	IBM PowerXCell8i 2.8GHz	
メモリ	4GB	

表 3 サンプル

分類	ファイル名	説明
サンプル画像	Piv03_1_256.bmp Piv03_2_256.bmp Piv03_1_2000.bmp Piv03_2_2000.bmp	入力サンプル画像 256pixcel × 256pixel, 2000pixcel × 2000pixel が用意されており、それぞれが時間変化した画像と対になっている。
出力ベクタ	Piv03_2000.vec	出力サンプルベクタ
サンプルコード	PIV256.c PIV2000.c timer.c	入力サンプル画像 256pixcel × 256pixel, 2000pixcel × 2000pixel を処理するためのプログラム。
その他	Readme PIV2000.exe in.par256 in.par2000	コンパイル結果と、実行時に入力画像を指定するためのパラメタファイル。

Speed-Up Evaluation using Cell/B.E.(2/8)



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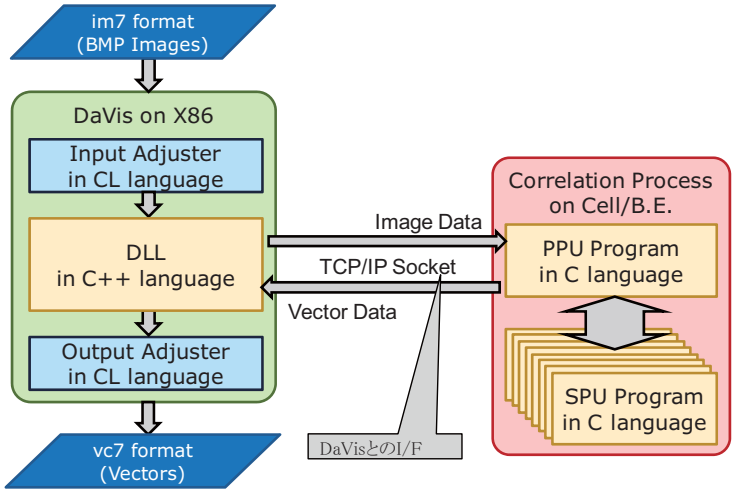
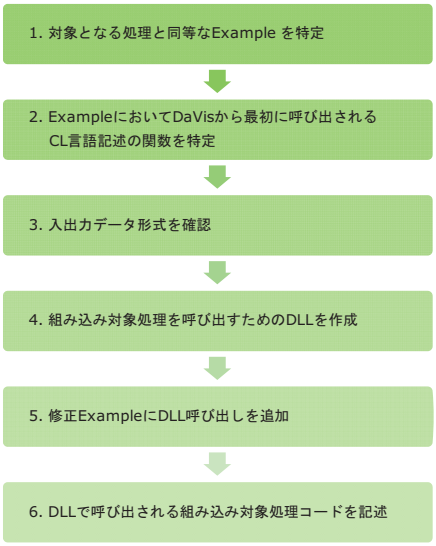
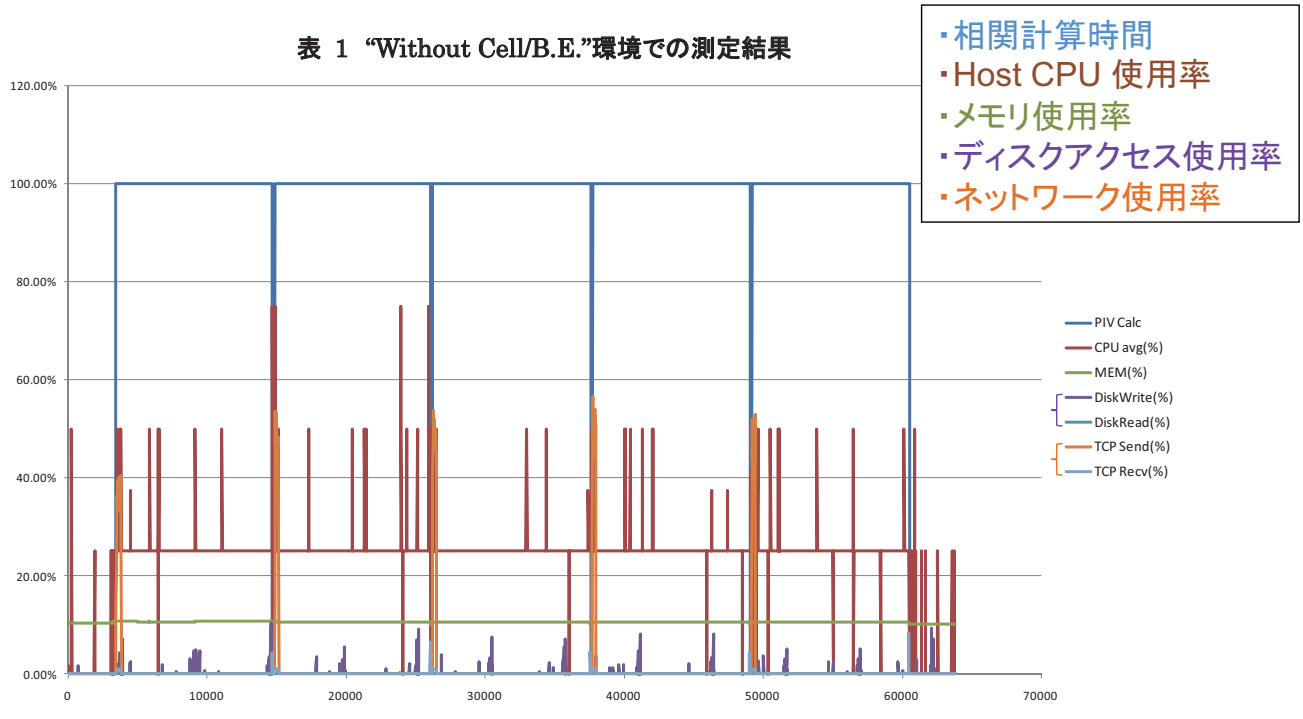
Speed-Up Evaluation using Cell/B.E.(3/8)





Speed-Up Evaluation using Cell/B.E.(4/8)

表 1 “Without Cell/B.E.”環境での測定結果



横軸は時間[msec]を示す

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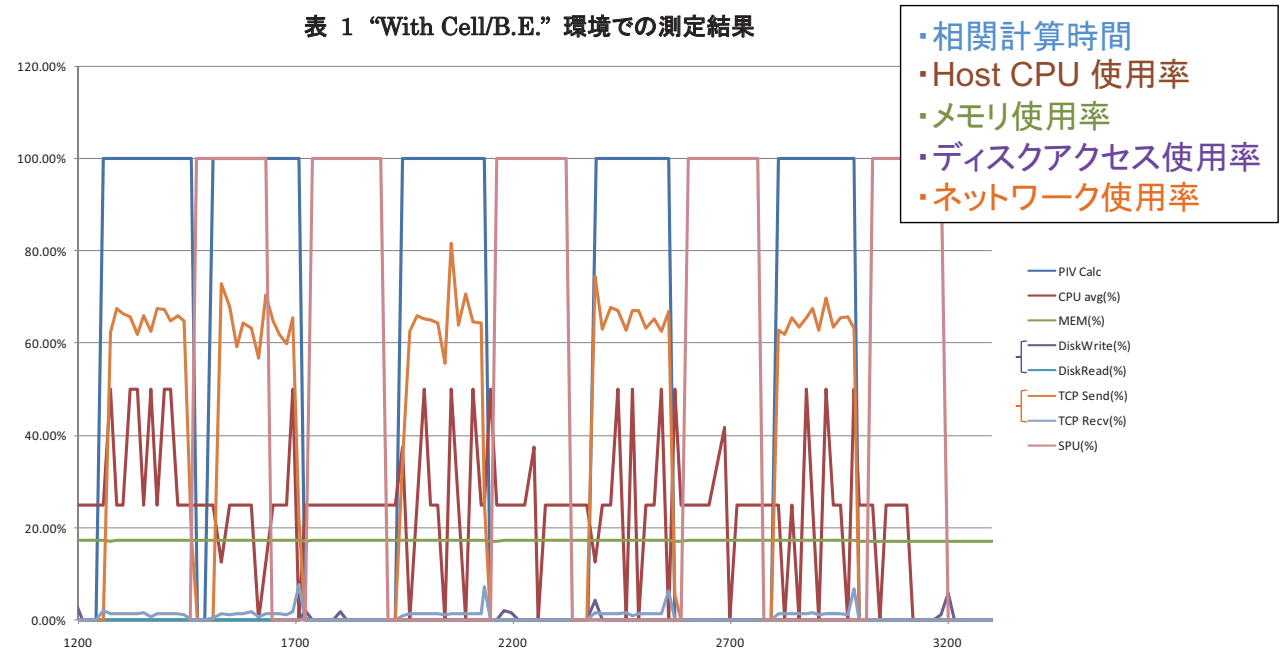
Speed-Up Evaluation using Cell/B.E.(5/8)

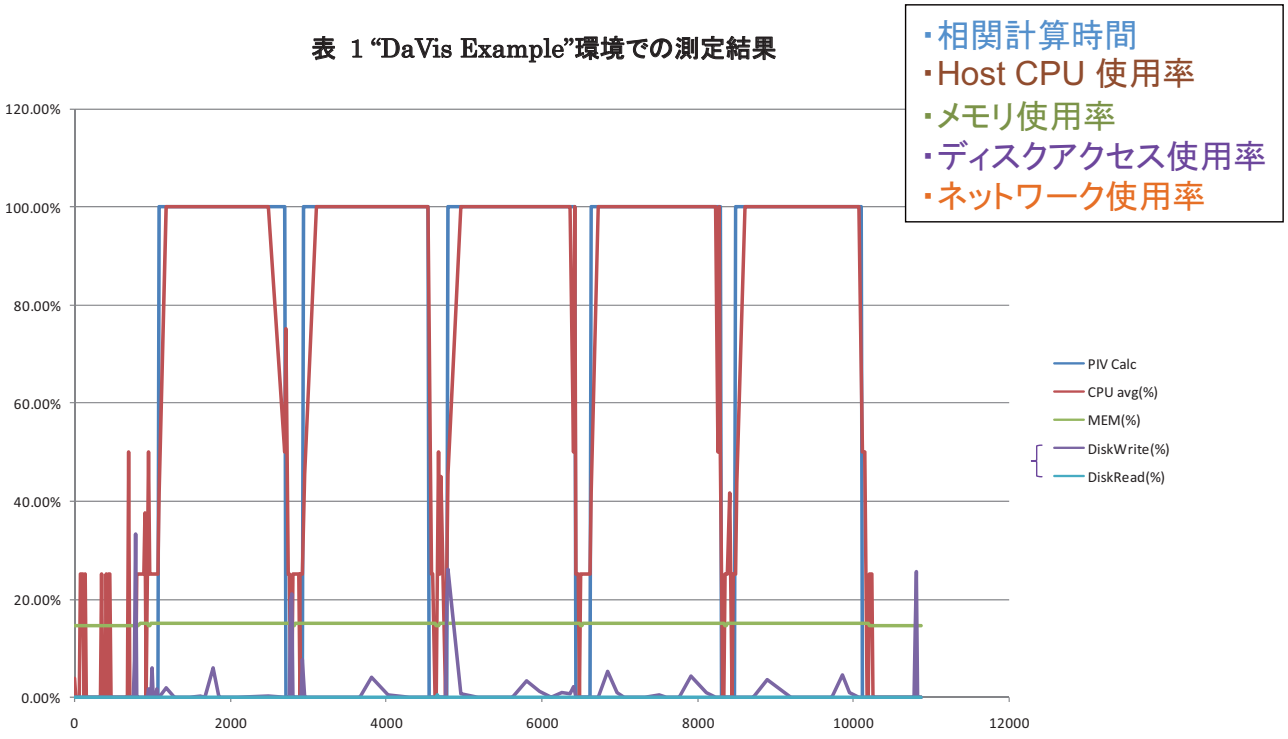
表 1 “With Cell/B.E.” 環境での測定結果



横軸は時間[msec]を示す。

Speed-Up Evaluation using Cell/B.E.(6/8)

表 1 “DaVis Example”環境での測定結果



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Speed-Up Evaluation using Cell/B.E.(7/8)

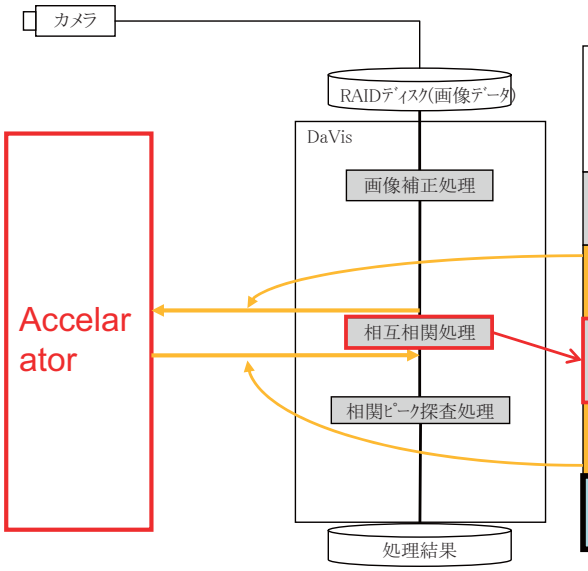


図　PIV処理要素概要

表　2D PIVにおける各処理の時間

PIV Processing Item	Processing Time [ms]		
	Direct Correlation		FFT
	Without Cell/B.E.	With Cell/B.E.	DaVis Original
画像補正処理 相関ピーク探査処理等 (前処理／後処理)	126	221	216
画像転送	298	194	-
相互相関処理	11010	#173	1647
ベクトル転送	20	11	-
処理周期	11454	426	1863

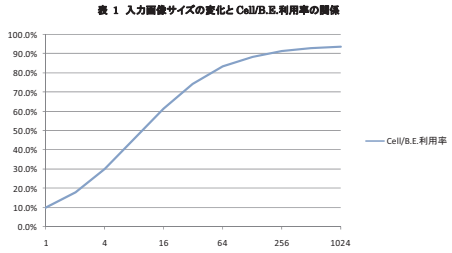
×26.9倍　×4. 4倍

(注)#の処理時間は画像転送処理と並行して実施できるため、処理周期には加算しない。

Speed-Up Evaluation using Cell/B.E.(8/8)

今後の高速化の可能性

・相関処理を倍精度(double)から単精度(float)で実行すると1.08倍高速化される
・Cell/B.E.とhostCPUとの接続を1Gbps EthernetからPCI Expressに変更することにより、1.7倍高速化される。
・2011年には、現行の5倍の性能を持つPowerXCell32ivが使用可能となる。
・Cell/B.E.を同時に複数使用し、高速化する。



その他の考察

・8MBの画像ファイル処理ではCell/B.E.をフルに使用していない。処理周期を延ばさずに、画像ファイルサイズを大きくすることができる。
・5年後にCell/B.E.とhostCPUとの接続が100Gbpsの帯域に達すると予想すると、処理周期は、相関時間が支配的になり、DaVis Exampleの数十倍程度の高速化が実現すると予想される。

今後のPCクラスタの高速化要因

・マルチスレッド化による相関処理の高速化

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Future Work on Speed-Up PIV

•GPGPUでの高速化の評価も実施する必要がありそう。
→CUDAによる評価では、Cell/B.E.と同等ないしは2倍程度の高速化が見込める。
但し、*Scalar Processor(SP)・Streaming Multi-Processor(SM)・Device Memory・Shared Memory・Block・Thread・WARP-unit*などの多数のGPGPUの概念を理解してチューニングをする必要があり、プログラミングにスキルを必要とすると共に、適用可能なアプリケーションが限定される。
→ディレクティブ挿入型のコンパイラが市販され始めたので、速度性能を評価する価値あり。

•FY21Q1末までには、どの高速化手法でDaVisを高速化するかを決定し、残りの期間は、高速化の実装を行う。

•高速化の実装方法について、ハイブリッド風洞利用者が持ち込んだアルゴリズム＝ソースプログラムを、高速化できるシステム（システムの上流工程まで柔軟性を持たせるシステム）とするのか、システムがあらかじめ用意しているアルゴリズムを利用者が選択して利用システム（上流工程は固定されたシステム）とするかによって、実装のための仕様準備や作業内容が変わってくるため、検討が必要である。(アナログ風洞の高速化のみならず、ハイブリッド風洞構築全般に言えること。)

Conclusion

- What is PIV?
- Motivation of Speed-Up PIV

At the measuring time・・・
＞From check of effectual measurement setup
To evaluation of phenomenon
＞To realize comparison with CFD results etc.
＞Additional measurement reflect from measurement result

- Candidate of Accelarator and Evaluation of Cell/B.E

Accelerator	Point	Speed-Up	Price	Stable Supply	Operation Cost	User Env.
Cell/B.E.	6	○ : × 26.9	△ : 1M JPY	△ : 3 suppliers	△ : "Professional"	△ :
GPU	5	○ : × 40	○ : 0.2 JPY	× : 1 supplier	△ : "Professional"	× : "CUDA"
FPGA	4	○ : × 100+	× : 5M+ JPY	○ : E. Appliance	× : "Craftsman"	× : HDL
PC cluster	(7) ← ×	: × 10	△ : 2M JPY	○ : PC	○ : De facto	○ : De Facto

○：2point、△：1point、×：0point

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パネルディスカッション
「Can EFD/CFD Integration Minimize Uncertainty?」

パネリスト（登壇順）： Andrew Meade（William Marsh Rice University, USA）
Edward N. Tinoco（Boeing Commercial Airplanes , USA）
佐宗 章弘（名大工）
越智 章生（川崎重工業）
口石 茂（JAXA）
司会： 吉田 憲司（JAXA）

吉田：JAXA の吉田でございます。これから僭越ながら本パネルディスカッションの司会をさせて頂きますので、宜しくお願い致します。本日はこのテーマを頂きましたが、特に不確かさということにつきまして皆さんで議論をして、今後この EFD/CFD 融合という流れでどこまで何を目指すかということを話し合って、出来れば課題の幾つかについて JAXA や研究者の皆さんが実際にアプローチして頂けるのを狙いたいと思っております。ということで、フリーかつフレンドリーなディスカッションを期待いたします。

まず最初に自己紹介でしょうか。Meade 先生と Tinoco さんはもうご紹介がありましたが一応簡単な自己紹介と、パネラーの皆様方はご自身の研究のフィールド等を簡単にご紹介して頂きたいと思います。その後に今日のパネルディスカッションのメインテーマ、“Can EFD/CFD integration minimize uncertainty?” につきまして JAXA の口石が資料を用意しておりますので、それを簡単にご説明致します。その後今日のパネリストのうち佐宗先生と越智さんからも簡単なプレゼンを頂いてからディスカッションをさせて頂きたいと思います。それではお願いします。

Meade：Andrew Meade です。Rice 大学の教授をしております。私はデータ融合の航空宇宙分野への応用に関心を持っていまして、実験流体力学（EFD）、計算流体力学（CFD）やマシン・ラーニングの研究をしてまいりました。EFD/CFD 融合で不確かさを軽減する事ができるか、そしてその手法が実験を行う者にとって実験の向上に役立つか、また CFD を行う者にとっては CFD 技術の改良に役立つか、といったことを考えたいと思います。

Tinoco：Edward Tinoco です。先ほどお話をいたしましたが、私の関心は CFD と EFD の両方にありまして、これらを一緒にすることによって両方の精度が増し、理解も深まると確信しております。

佐宗：名古屋大学の佐宗と言います。立場としては EFD サイドだと思います。今回のワークショップは色々な分野の発表が見られるのですが、今日の話に限っては航空機のデザインということ

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にかなり特化している内容だと思いますので、自分の立場としては航空の関係する流体の中の実験と計算ということで少し話をしたいと思います。宜しくお願いします。

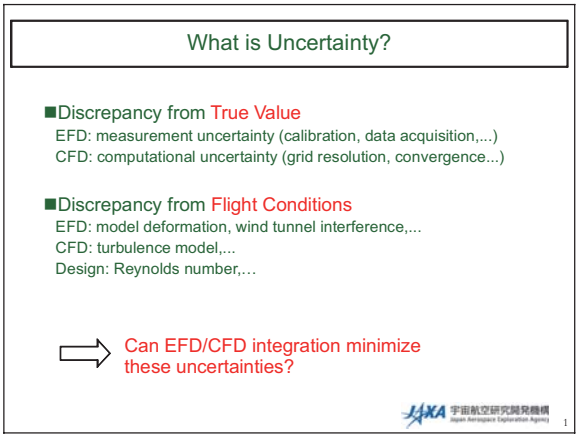
越智：川崎重工の越智と申します。入社して 12、3 年くらいずっと CFD がメインで、後は風洞試験もやってきまして CX とか PX などの開発に携わってきました。今日はメーカー側の視点から何か意見が言えればいいかなと思っております。

口石：JAXA の口石と申します。私は大学の時はずっと CFD をやっていまして、卒業して JAXA の前身であります航技研に CFD と風洞試験の橋渡しのようなものをやってくれということで雇われました。それから 10 年近い年月がたったのですが、結局自分はそういうことに関して何もやってこなかったということを今さらながらに気づいて、俺は今まで一体何をやってきたのだろうと自戒の念を込めてパネリストに立候補させて頂きました（笑）。今日は実りあるディスカッションとなることを期待しておりますので、宜しくお願い致します。

吉田：ありがとうございました。先ほど申しましたように、最初に口石の方が立候補しただけのことはありまして資料をしっかり作ってきましたので、まずプレゼン頂こうと思います。宜しくお願いします。

口石：長丁場のパネルディスカッションは得てして議論が発散する傾向にあると思いますので、一つのテーマの流れに沿って議論をしていきたいという希望から事務局で相談してこういった資料を用意しました。“Can EFD/CFD integration minimize uncertainty?”とタイトルが漠然としているので議論も漠然としかねません。まずは言葉の定義をしっかりするために、uncertainty と EFD/CFD 融合という 2 つの言葉の定義を最初にしておきたいと思います。

最初に uncertainty ですが、これは色々な分類の仕方もありますし先程の Tinoco さんの発表の中にも同じようなことがありましたが、皆さん基本的に考えていることは同じだと思います。今回ここにいらっしゃる方は大方航空宇宙分野に関わっている方だと思いますが、そういった視点から考えると大体こういった形に大別できるのではないかと思います。



最初ですが Discrepancy from true value ということで、これは要するに真値からのずれという意味での不確かさ。これは EFD/CFD それぞれ考え方はあると思うのですが、EFD につきましては計測の不確かさということです。EFD とは例えば風洞試験なら風洞試験で何らかの物理現象を計測するということですが、計測には大方何らかの不確かさを含んでいますといった意味での uncertainty です。では具体的に EFD でどういった不確かさがあるかというと、較正に起因する不確かさであるとか、データ収集（data acquisition）における不確かさであるとか、それからデータ処理（data reduction）の時、生データから何らかの物理量に換算するときに何らかの不確かさを含むといったように一連の測定プロセスの中で色んな不確かさ要因があってそれがどんどん蓄積されていくという、これが基本的に EFD における不

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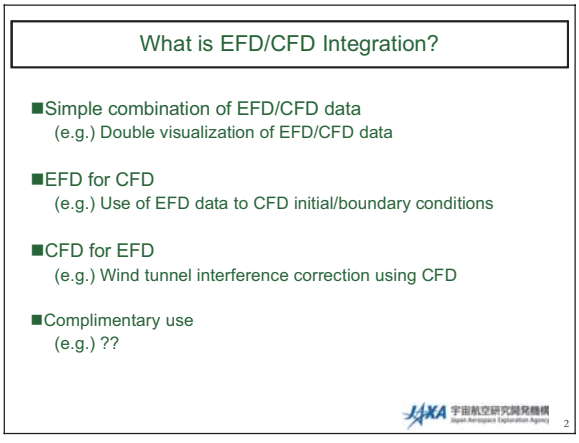
確かさなのだろうと思っております。それからCFD につきましては、支配方程式を離散化して数値的に解くときに本当に正しく解けているのかということです。具体的に言えば計算空間を格子で分割して解くのですが、それが十分分割できているのかという格子収束性の問題がある。また反復解法によって解を求めていくとしてきちんと収束解が得られているのかという収束性の問題もあって、実際に数値計算で何らかの答えを出そうと思っても常に正しく求められているとは限らない。さらに CFD の物理モデルが、例えば実際の流れとか飛行条件における乱流現象を本当に正しく反映しているのかどうかという問題もあるかと思います。これらが CFD にとっての Discrepancy from true value という意味での uncertainty です。

さて仮にこの EFD/CFD それぞれにつきましてこういった誤差がなかったとしても、例えば EFD については計測すべき対象を全く誤差なく計測できているとしても、CFD につきましてもきちんと方程式を離散化して方程式を解いてきちんと正しい答えが出ているとしても、それが実際に我々の求めている答えなのかというと必ずしもそれはそうではないだろうということもあります。何が言いたいかといいますと、我々が最終的に求めたいのは航空分野に特化して言えば実飛行条件における空力性能ということになると思うのですが、EFD で正しく測れてもそれが実条件フライトコンディションに直結しているということは必ずしも言えないという意味での Discrepancy from flight condition で、これがもう一つの大きな uncertainty になるのではないかと思っております。

これも具体的に言いますと、EFD につきましては風洞試験と言い換えても良いかと思いますが、風洞試験で正しく計測できたとしても実際には風洞の中で模型を入れますと模型が風圧で変形しますので、デザインした形状とは若干模型が異なってしまう。それからご存知のように風洞には壁がありますのでその影響が無視できない。それから模型を空中に浮かせることは出来ないので支持棒で支える必要がある。その支持棒があるというのは要するにフライトとは違う条件で計測を行っているということですから、風洞試験とフライトとの間にはギャップがあるということです。これが一つの uncertainty になるということです。それから風洞試験では飛行条件のレイノルズを再現することは一般には難しいということもありまして、こういったスケーリング効果というか、そういったものの uncertainty というものも含まれているということ。このように uncertainty を分類してみたのですが、問題はそれを小さくする為にはどういった手段があるのか。その一手段として、EFD/CFD を上手く組み合わせることによって諸々の uncertainty を minimize することが出来るのではないかということを考えたいのが今日のモチベーションです。



次にそもそも EFD/CFD 融合というのは何ぞやということです。これも色々な考え方があると思うのですが、大きく分けると 4 つくらいに分けられるのではないかと考えています。一番単純なのは EFD のデータと CFD のデータを単純に合体

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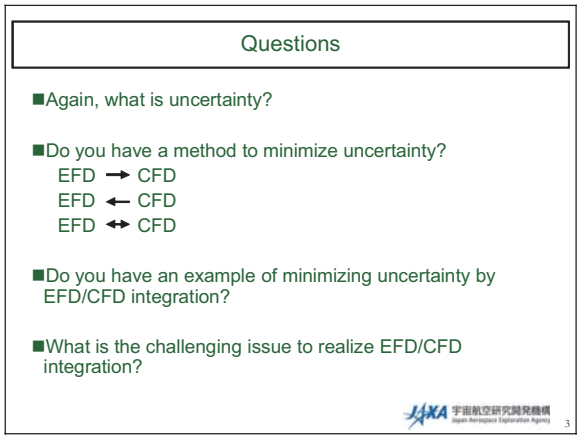
させるというアプローチです。例えば一つの画面で左側にCFDの結果を出して右側にEFDの結果を出して比較するとか、シュリーレン写真にCFDをオーバーラップさせることによって衝撃波の位置がどれくらい合っているかとか、そういったことが調べられます。それに対してEFD for CFDという言い方をしましたが、これは要するにCFDの精度を高める為にEFDを使うということ。具体的には風試データをCFDやEFDの初期条件や境界条件に用いることによってCFDの精度を高められるかもしれません。逆にCFD for EFDという観点では風試の精度を高める為にCFDを使いたいということで、これも具体的に言いますと、いわゆる風洞壁干渉の補正をCFDを使って行う等があります。このCFD for EFDとEFD for CFDの2つは、例えばEFD for CFDだったらCFDにはEFDによって恩恵を受けますが、EFD自体はCFDに対して何ら恩恵を受けないといったように一方通行的なプロセスを意味しております。それに対して我々が積極的に目指したいと考えているのは、お互いのcomplementaryな、双方向的な活用です。しかしながらその具体的な例は何なのかというと実は我々にはあまり明確な共通認識というのはないのかもしれませんので、ではどんなものがあるのですかという点について今日は議論できたらと考えています。



そういうことでuncertaintyについて定義とか分類をしたのですが、これで本当に十分なのか。他にあるのではないかとか、他の分類の仕方もあるのではないかといったことにつきましてご議論頂きたいということ。それからそういったuncertaintyがあるとして、それを具体的にminimizeするような具体的な方法があるのかどうかということ。EFDからCFDへフィードバックをかける、逆にCFDからEFDにフィードバックをかける、それからEFDとCFDを双方向的に活用する、この3つの観点から具体的な方法があるのかということを考えたいと思います。それも踏まえまして、本当にEFD/CFD融合手法として実際にuncertaintyを小さくしたような例があるのかどうかということについても考えたいと思います。それから最後ですが、EFD/CFD融合自体は別に今に始まったアイディアではなくて昔から色んな方が考えていたと思うのですが、実用化になかなか結びつかないのは何らかの障害とか技術課題といったものがあったからではないか、あったとすればそれは一体何であるかということにつきましても考えたいと思います。

吉田：どうもありがとうございました。会場の皆様、こういう主旨で今日は議論したいと思いますので、これを念頭に入れながら後でご意見等をお願いしたいと思います。次に佐宗先生の方からお願い致します。

佐宗：口石さんが話をまとめられた後でちょっと壊すような話をするかもしれませんが、予め打ち合わせをしていなかったのでご勘弁下さい。私は前回のワークショップでも話をさせてもらう機会がありまして、その時の資料をリバイズして話をさせて頂きます。

まず“Can EFD/CFD integration minimize uncertainty?”という質問に答えればすぐに懇親会かと思って、イエスと言えばそれで終わりだと

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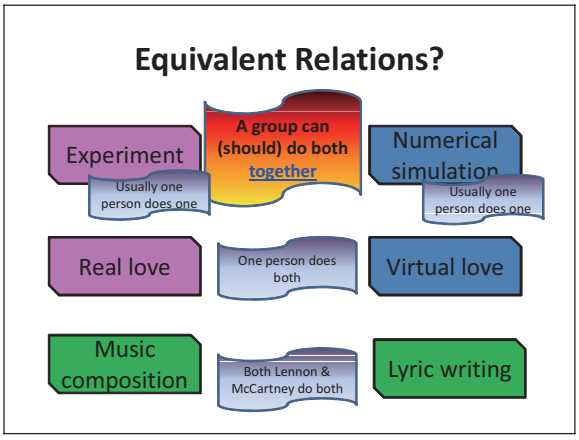
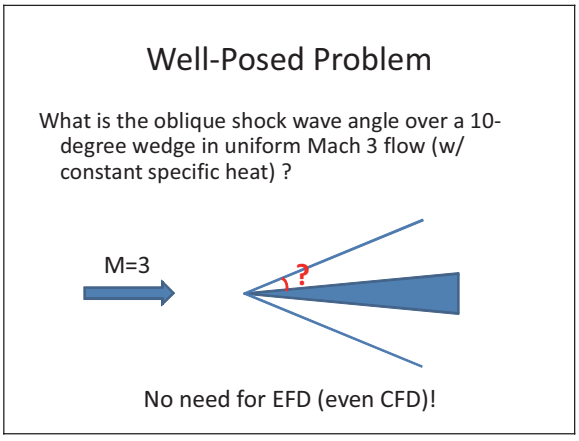
思っていたのですが（笑）、やはりすぐには答えが出せない。やはりこれは説明が少し必要だということです。前回は CFD と EFD はレノン、マッカートニーでないといけないというのがタイトルでした。ビートルズの曲の多くはジョン・レノンとポール・マッカートニーが作って、実際にはかなり一人で作ったものもあるし、コントリビューションはどちらがどちら、どちらが詩でどちらが音楽かということははっきりと分かれていなかったというか、両方とも両方やったみたいな話なのですが、要するに CFD と EFD を例えば詩と音楽の関係に置き換えて考えた方がよいのではないかということを話しました。



そしてもう少し具体的に言いますと、今の曲を作るということと歌詞を作るということは実験と数値計算です。うちでは研究室で新しい学生を入れるときに、「あなたは本当の恋愛をしたいか、バーチャルな恋愛どっちがいい？」「本当が良い」というと、「じゃあ君、実験しようよ」ということで「この研究室に来たらどう？」という誘い方をしています。ミュージックとリディックというのはどっちがリアルでどっちがバーチャルかということではないので色を変えているのですが、言いたいことはジョン・レノンとポール・マッカートニーはそれぞれが音楽も作ったし、歌詞も作ったということです。Both do both です。それで一人の人間が本当の恋愛をすることもあるし、本を読んだり考えたり映画を観たり、そういうバーチャルな体験もするわけです。そういう意味で一人の人間が両方やるということです。では実験と数値計算はどうでしょうかと言うと、普通は一人の人は大体どっちか。先程口石さんのお話にもありましたが、なかなか同時期に両方やるっていうほどそういうことが適切かどうかということも分からないし、普通は大体役割分担をした方が特に大きなことをする時には効率が良いというわけです。やはりこの 2 つを比べるとここはどうもちょっと問題があるのではないかというのがあったとして、ではどうすればいいかというと、グループとしては両方出来るでしょう。グループとしては両方やらなければいけない。この together というのが大事なのです。どういうふうに together かと言いますと、例えば同じ部屋でお昼ご飯も一緒に食べて、ディスカッションしながらやりましょうというようなイメージの together。やはりどこでもそうですが CFD の研究室は、大学もそうですが、CFD が主で、実験が主で、なかなか同じ部屋でやるとか、お昼ご飯くらい食べるかもしれませんが、それもなかなか実態として難しいのですが、そういうところで together というところが大事だと思います。



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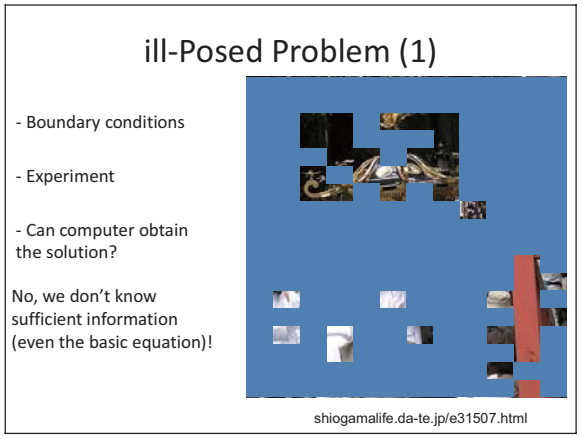
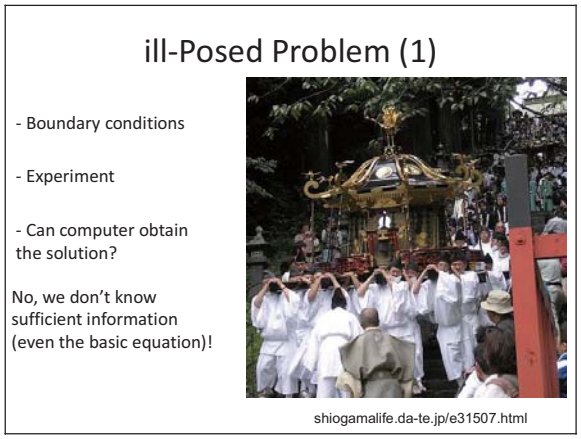
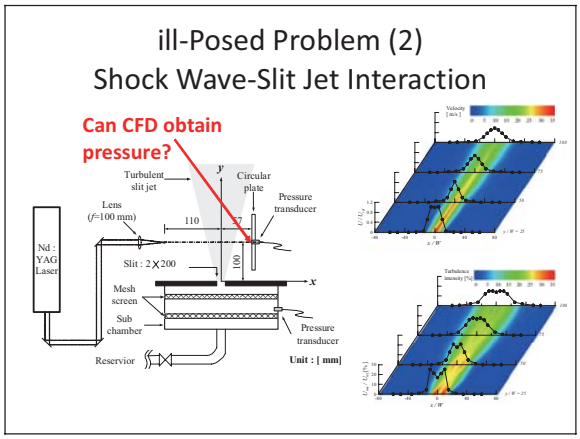
先程 Meade 先生のお話にもあったので釈迦に説法みたいな話なのですが、要するに integration が精度を向上できるかという話は問題の性質によってくると思います。例えば先ほど well-posed、ill-posed というお話がありましたが、例えば well-posed の例で超音速流れがあって、楔があったらショックの角度が何度になりますか。これももしγ＝1.4 だったら別に計算しなくても実験しなくても何もするまでもなく well-posed、条件を与えれば答えが一つに決まるということです。ただここに例えば比熱一定ではなくて段々マッハ数が上がっていって、比熱比温度の関数であったり圧力の関数であったりするとこれは必ずしも well-posed ではなくなってくる。段々ill-posed になってくるというわけです。これが well-posed に関する問題の極端な例です。





これは昨日一生懸命作ったのですが、パネルクイズ 25 というのを知っていますか？これは ill-posed の問題で、例えばこのくらいの画像しか見たことがなくてこれが境界条件・初期条件だとして、では何の絵でしょうといったら結構分からないのではないかと思います。ここで例えば実験をしてみる、少し可視化をしてみる。そうすると少しだけこのくらい分かったと。このくらい分かれば結構大体分かるのではないかと思うのです。これでも実験というのは全ての情報を与えているわけではない。それではこの絵が何を表しているか、コンピュータでシミュレーションしたら分かるかというと、これは絶対に分からない。どうして分からないかと言うと、これだけの情報ではユニークに決まらないことを我々は見ているわけです。多分これは何の写真かというのはここだけ見れば検討がつくと思うのですが、ではこの辺は何色で何が映っているかというと、これでは分かるわけがないのです。実際にはこれはお祭りでお神輿を担いでいる写真ですが、ここまでくると全部 well-posed になる。今度は逆にここの赤いところの一部分を隠しただけだったら、ここはかなり well-posed だから答えは恐らく隠れていても分かるということになると思います。



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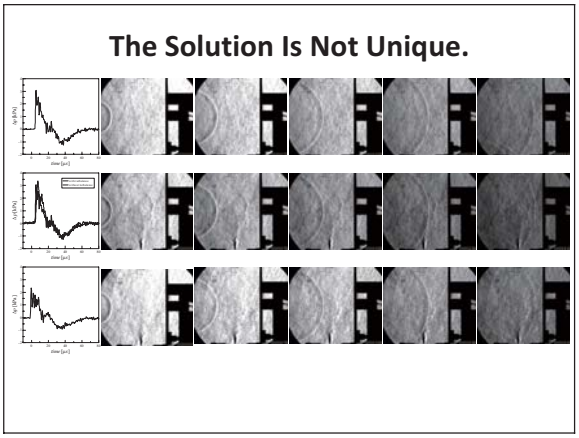

これはある意味で譬えなのですが、衝撃波と乱流の干渉という実験をやっています。その一例ですが、これはここがサブチャンバーになっていまして、このチャンバーがもっと大元では 1 立方メートルくらいの加圧した空気のリザーバーに繋がっていて、ここの中に流れが入ってくる。ここにスリットが上向きにありまして、このスリットの幅が 2 ミリ×奥手方向に 200 ミリ、20 センチ開いています。ここから噴流が出てくるわけです。ですからここの圧力を適当に設定すると噴流が出てきて、このスリット幅で換算してレイノルズが 4 万くらいになるのですが、そうすると shear flow で乱流が出てきます。平均場を図るとこれが平均速度で、大体出口から 5 センチ離れたところから測り始めて中心で流速が 30 メーターくらい。ですから出口なのでもう少し速くなっています。それからこれが乱流強度です。といってもこれは速度の RMS を代表値で割った値ですが、要するに速度変動を測るとこういう分布が出てきます。ではここでレーザーのパルスをフォーカスして、ここで火薬をパチッと発破させたのと同じように、弱いですが衝撃波を作る。そうするとここで測る圧力はどうなるかという訳です。こういう問題です。これはソニックブームへの大気乱流の影響に関する基礎的な実験です。それでここの圧力が CFD で予測できるかと何も見ないでできたらすごいと思うのですが、結論から言うと通常の意味では ill-posed に近い問題なので答を見てから計算しないといけないし、答を見る必要がある問題だと思います。結果はこうなります。一番上はスリットからジェットを噴出しない場合です。ここに圧力のゲージがここの先端にフラッシュマウントであるのですが、もし何もなければこの辺でレーザーフォーカスで作られたブラストウェーブがこういうふうに広がっていって、ここに反射してここで圧力が上がると。このようなブラストウェーブがあるところに正面に板を置いたらこうなるというような、ノイズは乗っていますがこういう物が出てきます。それから 2 つ重なっていて見づらいのですが、下の 2 つは全く同じ条件です。噴流を出すところのチャンバーを出すところの圧力も一緒だし、恐らく計った日も一緒だし、レーザーのエネルギーも一緒だし､全部一緒の場合です。こういう場合にも、これは 2 例しかありませんが 2 つ重なっているのは、1 つはこれがコピーしてあって、もう一つはそれよりも高い圧力というような結果です。そういうような時には、これはちょっと見づらいのですが、よく見ると、衝撃波の波面というのがもう少し曲率が変わっていて、ここの圧力センサーのところに当たるというような波形になっています。それから下の図は全く同じ条件で最初の立ち上がりの過重圧が低くなる時です。この場合にもこうなってこうなっていて、結局これはこの画像からこの画像を引き算した絵なのですが、引き算するとわりとショックが 2 枚分くっきり見えてくるのですが、このように波面にでこぼこ乱れがあってそれで圧力が変わる。結局強くなる時と弱くなる時があるというのは、噴流自体が平均場としては先程のホットワイヤーで計った特性があるのですが、実はもっと時間解像度をもって見ると乱流となって色んな大きさの渦が出ているというのもあるから、どのタイミングで

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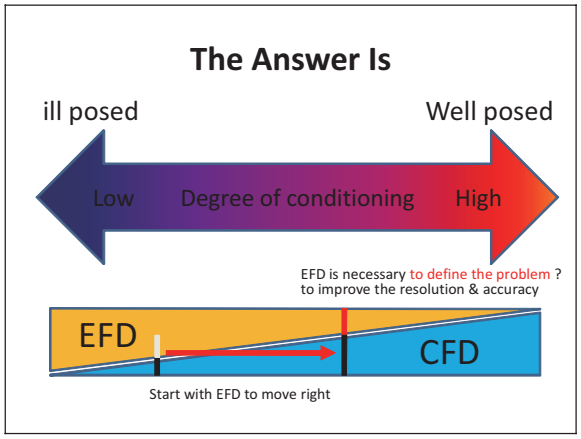
どういう状態のときにショックを通過したかということでかなり結果が変わってくるというようなものです。スリットジェットがある場合と無い場合で比較すればオーバープレッシャーの平均値は下がる。しかし標準偏差が非常に大きくなるので、これを足すと 3.5 になるからジェットなしよりも高い時もありうる。平均すると低いけど高い時もありうる。こんな結果になっています。これを CFD でがんばって解くのですかというのではなくて、これはまず実験の結果を知って、それからそれはどういうことが原因かとか噴流はどうなっているかということを計算して、答えを知ってから中を見ていくということが正しいやり方なんじゃないかと思います。



言いたいことは、要するに ill-posed、well-posed の問題があって、well-posed の問題であれば本当に 100%であれば CFD だけで、後は CFD の解像度とか計算のコストとかそういう話で全て済んでしまう。それから先程の写真みたいに絶対に分からないというようなこともあって、これはまず実験をして情報を知るということが最初にやるべきことだと。今の議論はどの辺にあるかはともかくとして、その中間のところを我々はやはり問題の対象にしているのではないかと。例えば、飛行機の形状が決まって全て決まると言っても、じゃあ全部ダイレクトシミュレーションをするかというとそういうわけではなくて、やはり例えばドラッグが、あるいはリフトが 1 カウントの精度で分かればいいといった場合と 10 カウントでいいといった場合と 0.1 カウントじゃないといけないといった場合と、これはどこまでの情報が必要かということは変わってきますし、そういう意味では飛行機の問題も全部 well-posed の問題では決してなくて、やはりこの辺のどこかにあるのではないか。結局言いたいことは実験と計算は一緒にやらなくちゃいけなくて、まずは実験をして実験の情報を入れてから数値計算をする。数値計算をすると数値計算の足りないところが出てくるので、またそれに見合う足らない部分の実験をするという。それでどんどん右側にいって全部分かるというようなイメージで一緒にやるということが大事なのではないかと考えました。

吉田：どうもありがとうございました。答えが一つ出ているような気もしますが、もう一つ越智さんの方から補足のプレゼンを頂ければと思います。

越智：スライドを準備してきていないのでその場でしゃべらせて頂こうかと思います。私の経験としてはハイブリッドという話が最初に頭にあったのは 10 年くらい前なのですが、CFD のデータと風洞試験のデータがなかなか合わなくて、当時は風洞試験の方が正しいと思われていたところもあって、「CFD 側でどうしてそれが風洞試験と違うのか、それを直せ」と言われました。随分悩んでその時は上手くいかなくて結局出来なかったのですが、それから暫く経って実は風洞試験の方が間違っていて、風洞試験の方を直すとちゃんと CFD と揚力－抗力のポーラーの形が合うということが分かって、そこから急速に CFD が社内でも使われるようになってきたという経緯がありました。何を言いたいかというと、ハイブリッドを

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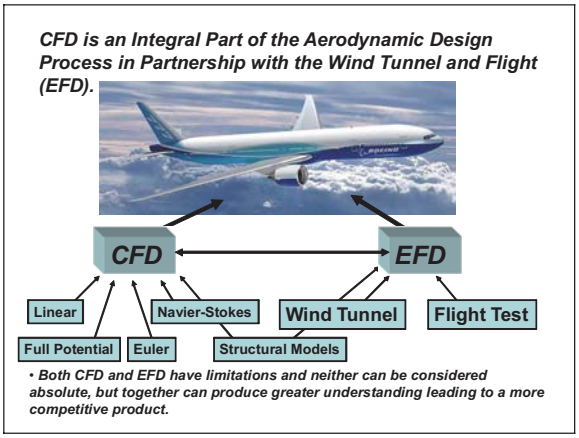
する時にまず基本的にお互いがちゃんとしてないと上手くいかないと強く感じています。例えば皆さんに部下が二人いて、A、B、C、D、E クラスあって、A クラスの人が二人いればその二人に一つの仕事を任せると恐らくAプラスくらいの結果が出てきて、B クラスの人二人に任せると、B 足す B は A くらいになるかな。C 足す C だと恐らく B か C。ところが、E クラスの人二人に任せると恐らくDではなくてEマイナスとかそういう結果が出てくるのではないかというところで、そういう意味で現状の CFD と風洞試験というのは恐らくBとかCとかその辺りくらいにいるかなと思います。そういう意味では時期的にはハイブリッドするには良いのかと思います。もしお互いがすごく発展して、お互い A になってどちらかやればそれで終わりになるという話になれば、またハイブリッドにするメリットというのもそれほどないのですが、そこまではまだ達していないというふうに思っています。後は不確かなものと不確かなものを 2 つ用意してそこから何かをより良くしようというのが基本的には非常に難しくて一昔前は私も悲観的になっていたこともあるのですが、一つ良い話はお互いに風洞試験で不確かな話、今までたくさん出てきたのでもう挙げないですが、この風洞試験で不確かな話と CFD で不確かな話というのはちょっと種類が違うのです。そこを上手く突いてやって色んな追加の試験なり追加の解析をすることで、確からしさを増していくということは出来るかと思っています。

最後に、ハイブリッドにするということが重要だと思うのですが、まずその前に各々EFD の人は EFD を、CFD の人は CFD を省みてしっかりやるというのが大切ではないかと思います。その一方、私はどちらかと言うと昔 CFD の人間だったので風洞試験の結果はわりと無条件に信じてしまっていたというところがあって、逆に風洞試験側の人から見ると CFD は正しいのではないかという認識があって、お互いがお互いをよく知らないと上手くいかないというところがあります。私も風洞試験が分かるようになってからは色々出来ることも多くなってきたので、そういう意味で昼ごはんを一緒に食べながらとか机を隣にしてやるとかすごく大事なことで、もしくは人が入れ替わってやったりするというのも良いことなのではないかと思っています。

吉田：どうもありがとうございます。これでまず、パネラーの皆さんがお持ちの見解をということでご説明させて頂きました。最後に Tinoco さんが用意してくださった資料がありましてその後にディスカッションしますので、宜しくお願いします。



Tinoco：CFD と EFD は既にパートナーです。航空機設計を進化させる方法はこれしかありません。我々は EFD、すなわち飛行試験と風洞試験のフレーバーの違いを知っています。模型と実機の構造の違いは非常に重要です。どちらの試験も真値は測れません、というのは我々はそもそも真値がいくらなのか分かりませんから。しかしこれらを組み合わせて考察することは重要です。

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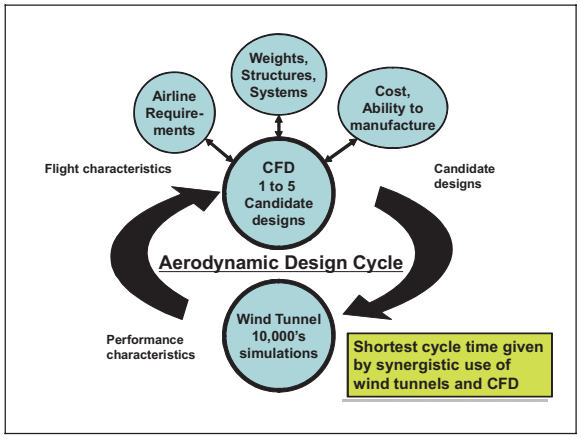
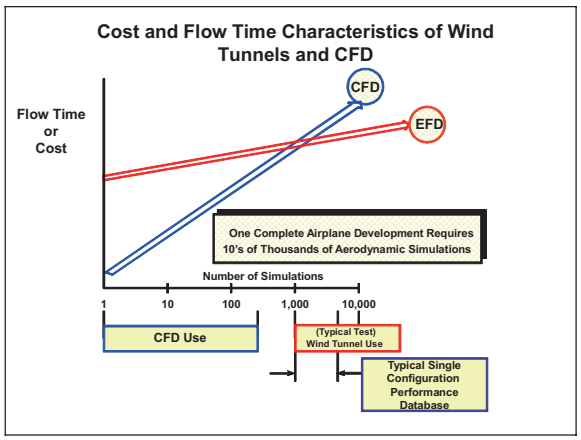
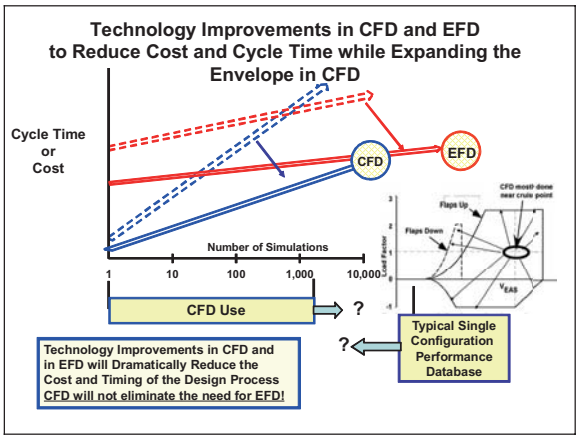


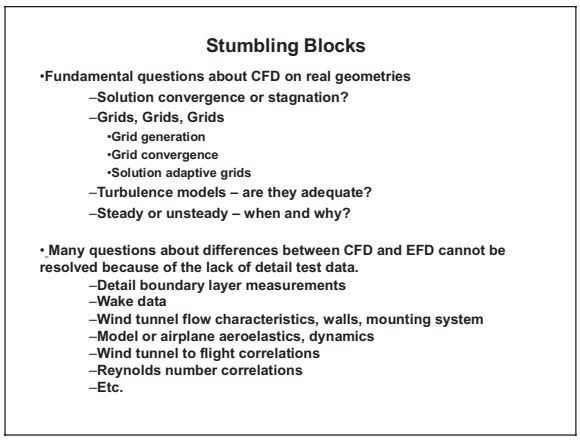
一つ考えなければならないのは、どのように使うかです。典型的な航空機の開発にはこのような設計サイクルがあります。航空会社側からの要求、構造、システム、製造コストなどが与えられると、我々は CFD を大々的に用いて設計の候補案を出し、それらの候補のサブセットとして風洞試験を計画します。何万点というデータポイントの風洞試験です。そこから必要な情報を得て、CFD と組合わせて動作特性や飛行特性を割り出します。このサイクルが迅速に実施できるほど多くの事が分かるし、CFD と風洞試験を一緒にすることでさらに多くの事が分かるのです。



今日では 100 から 1000 のオーダーの数値シミュレーションができますが、シミュレーションは実施回数に比例してコストが増大するので、すぐに風洞試験と同じくらいの時間とコストになってきます。風洞試験の場合には初期コストが高くつきますが、一度模型ができると何千というデータがとれます。



そこでできると良いのは、CFD と風試の両方にかかる時間を減らすこと、つまりこのサイクルを早くこなす、もう一つサイクルを追加してより多くが分かる、より早く製品化に到達することができるといったことです。さらに高速化だけではなく、CFD をより広い flight envelope で使えるようにすることも必要です。



さて、何が障害となっているのか？ CFD に多くがありますね。解は本当に収束しているのか、それとも収束の前にある値に留まって収束には程

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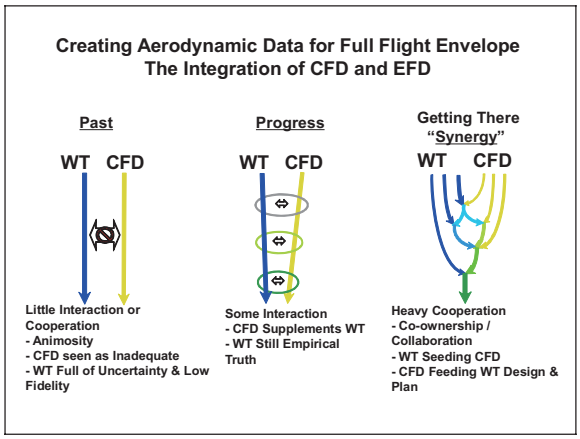
遠い結果になっているのでしょうか。計算格子にはこれで良しという終わりがありません。格子収束、格子生成、解適合格子、等々。格子収束については Drag Prediction Workshop でずっとやってきましたが、まだ十分ではないと思います。2 次元だったらできているのですが、3 次元計算の場合はまだ本当に収束しているかどうか分かりません。乱流モデルの精度は十分でしょうか？格子や収束の問題に答えていないのであれば、これらの乱流モデルが適切かどうかも分かりませんね。非定常シミュレーションをどんな場面で使うか？ LES をどの場面で使うか？ こんな訳で CFD には多くの疑問点がありますし、それも含んだ上で EFD との違いがあるのです。

また、境界層計測は十分にできていないですね。単純な実験ではできていますが、複雑な実験とか 3 次元の航空機形状ではどうなのか？ 後流データについても本当に少ししかありません。風洞の流れ特性、これもある程度計測は行ってそれなりのデータはありますが、全ての境界条件が分かっている訳ではないし、といった所です。これらのことはいつも疑問点になっていて、全ての境界条件を完璧に与えて問題を完全に解く事など決してやっていません。そこで本当のところの問題は、これらの不確かさがいかほど重要なのか、そしてこれらが最終製品に何らかの影響をもたらすかなのです。もし製品に違いを生じさせないのであれば、こんなことで時間を浪費すべきではありません。もし影響があるのであれば、正しい解が何なのかについて詳しく調べるべきでしょう。

過去、CFD コミュニティと実験コミュニティは分かれていて殆ど言葉を交わしませんでしたが、今日は両者のコラボレーションが増えています。お互いに言葉も交わします。まだまだ別行動しがちではありますが、現在はシナジーに近づいています。そして CFD で試験計画の支援や結果の補正をしたり、あるいは風試データを CFD の改良に用いたり、CFD と風洞試験は一緒に活動しています。



そしてここに至って、これらを一緒にすることでより迅速な判断を可能とするデータ融合という考えが出て参ります。何故ならば、CFD、EFD ともにその目的は航空機の形状はどうあるべきか、安定性と操縦性能を保証するのに十分な強度を有する機体構造はどうあるべきか、といった設計上の判断を可能たらしめることだからなのです。その為にこんな事をしているわけですね。実際、顧客の航空会社は圧力分布がどうであるかなんてことに興味はない訳です。彼らの関心事は安全性と経済性だけで、設計過程で出てくる詳細は別の誰かが心配することなのです。もっとも我々が安全性や経済性を実現する為に知らなければならないのは、それらの詳細な部分なのですが。

吉田：ありがとうございました。少々長くなってしまいましたが、これからディスカッションをさせて頂きます。ポイントとしては EFD/CFD が目指すところに関する皆さんのお考えは多分ほぼ一緒で、そうすると不確かさは何であるか。それは例えばリアルフライトとの差と見るのか。あるいは物理モデルの差と見るのか。色々な議論があると思います。そしてそれをどういうふうにやる

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かというと、一緒に食事を食べるというところから始まって、さらにシナジーというところまで持っていくというところで、目指す議論は同じだと思いますが、まず会場の皆さんからこのパネリストの方、あるいはご自身のご意見も含めて何かまず問題提起でも結構ですが、ご発言ありますでしょうか。

会場：CFD と EFD の融合の先にあるのは、例えば CFD は EFD の uncertainty を減らし、EFD は CFD の uncertainty を減らしていった結果として、complete agreement に到達することがそもそもの目的なのでしょうか。口石さんにお伺いすべきだと思いますが、融合の最終ゴールというのは一つの真値に到達することなのでしょうか。

口石：究極的にはやはり真値を求めるのが目的でしょうが、完全に一致するようなデータというのはまず得られないだろうというのが大前提だと思うのです。その上でその時代に応じて、これぐらいの精度は必要だという要求は当然出てくると思うのですが。航空機に限って言えば、やはりドラッグが何カウントくらいのオーダーでエラーバーが出せるのかといった目標を具体的に定めるというのが大切で、今具体的に航空機メーカーがどれくらいを求めているのか、それで決まってくると思うのです。それはどれ位なのでしょう。現時点ではプラスマイナス数カウントくらいで自分が求めている解がこの範囲内にありますと EFD/CFD 融合で言えることが目標なのではないかと思っています。それが将来、究極的には 0.1 カウントくらいのオーダーにまで行くのかもしれないのですが、その時その時の要求精度を踏まえて方法論を見直していって、具体的な目標値に向かってどういうふうに融合を進めていくかを考えていくことが大切なのではないかと思います。

会場：Tinoco さんと越智さんにお伺いしますが、CFD と EFD がアグリーした解を与えるということはデザイナーから見た時に究極の目標ですか。設計者は恐らく実フライトのデータを欲しがるのではないかと思うのですが、今のところ CFD はずっと風洞試験データを再現する努力をしてきている。これから先、設計者は実飛行条件におけるデータがどうなるのかを求めるのではないかと思うのですが、それは正しいことでしょうか。

越智：私の立場からすると、風洞試験と CFD とが一致した答えですといったデータをもらうことにはあまり意味はなくて、フライトでどうなりますというのをもらうというのが一義的だと思います。ただ現実的にはフライトのデータを見積もるというのはそれはそれで難しい話で、基本的には風洞試験が CFD のデータからどれくらいずれがあるというのを各メーカーとも持っていて、そこでシフトしてやる。そういう意味では、CFD と風洞試験が一致していればそこからの較正というのはやり易い。後はどれくらいの精度がいるかという話になると、空力の精度として良いことに越したことはないけど、例えば重量で見ても実際作ってみたらどれだけ重量が違っていたというのはある程度誤差はあるので、基本的にはそれよりも小さければ良いに越したことはないけど限界というのは当然あるのかと思っています。

Tinoco：CFD と EFD の融合で重要なのは、どうしてそれらの結果が異なるのかを理解することだと思います。おっしゃる通りで両方同じとなるように試みてもおそらく見込みがないでしょう。違いが多すぎます。それよりもなぜ異なるのかを調べ、それらをどう航空機に応用するかについてより良い理解を得ることです。結局重要なのは実際の航空機ですから。

我々はいつも相対的な計測をしています。風洞試験結果を実飛行に適用します。実飛行でも計測します。スケーリングファクターを風洞試験から実飛行を推定する為に適用します。スケーリング

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が大きければ大きいほどリスクが大きい。これらのスケーリングファクターを小さくしたいのです。CFD と EFD の融合はその助けになる筈です。また、どちらかを信じるべきではないかといった事を指摘するのにも役立ちます。ですから我々は融合を続けていく必要があると思いますよ。再度申し上げますが、必要なのは理解なのです。速く理解できればできるほど設計サイクルは早まり、より良い製品を製造できるのです。

吉田：今の件に絡んででも結構ですし、また別のご意見でも結構ですが、何かありますでしょうか？

会場：佐宗先生のお話に関連してちょっとお聞きしたいと思ったのですが、先程の乱流と衝撃波の面白い写真を見せて頂いた時に、こういうようなものは実験でやるべきだろうと。要するに、計算では分からないというようなお話をされたと思うのですが、これというのは原理的に CFD は出来ないという意味なのか、それともこれは実験してしまった方が早いという意味でおっしゃられているのか。その辺に興味があったのでお聞きしたいと思います。

佐宗：最後の図で、要するに well-posed、ill-posed、ill だったらまず実験かということを見せたのですが、その考え方でいくと最初何も分からない時には実験をするとああいう結果が出るということが分かると思う。ですからさっきの図の左から始めるべきであると。ところがあの実験結果が出てしまったら皆実験結果を知ることになるわけですから、その立場はどんどん右の well-posed に近づいてくるのです。そこからは正解に辿りつく時に、まず実験も何も見ないで CFD をやると回り道になるけれども、まずここまでは実験結果に合わせたような答えが出るようにやってみましょうというようなところから始めれば。だから問題としてはこれはスリットの形が決まっていて、要するにチャンバーの中の気体が理想的な乱れのない、あるいはどの程度乱れがあるか分かっているものであれば恐らくかなり何も見なくても答えが出ることになると思いますが、実際に噴流として出てくるサブチャンバーの中の乱れ状態とかそういうのは分からないわけで、実験でも定義をしていないし計算でもアプリオリには定義できないものですから、まずは結果を知ってから中がどうなっているとかそういうところを掴んでいってということになるのではないかと思います。だから実験でも全部が定義できるわけでもないし風洞で一様流が出るわけではないですから、やはりそれも全部含んで評価をしないといけないし、その時に CFD であれば理想的な状態はこうなるけれども例えば乱れが入ったらこうなりますとか。先程 Tinoco さんの感度に関するお話で衝撃波の場所がすごく敏感に変わるところがあって、ここのデザインがすごくセンシティブに効くのだとか。今のお話で言うと、チャンバーの中の乱れがこんなに外の状態に効いてくるのだということも含めて、今度は実験だけでは情報が足らない。なんとなく合うような計算をしてみて中がどうなっているか、どれがどういうふうに効くかというところを手探りで一緒に探っていくというようなことで、正解というか理解を深めることに辿り付くのではないかと思います。

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会場：ということは、やはり効率とかそういうようなところですか。計算だったら片っ端からいくら CPU 使っても構わないといってやれば、きっと何か出てくるだろうと思うのです。でもそれをやったらどう見てもサイエンスのやり方としてはあまりにも効率が悪い。やはり実験をやった方がいいでしょうという理解に結局はなるのでしょうか。

佐宗：先程の実験ですと実はもう 10 年位前にアメリカの音響の人がやられていて、我々の実験もその結果に合っています。合っているという意味は、平均的には圧力が落ちて RMS のばらつきは一桁以上上がる。そういうところは合っている。しかし実際は要するに、乱流源としている装置自体は我々の使っている装置の乱れと恐らく彼らが噴流を出したところのプロセスも機械も違いますし、中の流れの状態も恐らくかなり違っていると思いますから、そうすると正解というのは何かということになってしまう。本当に静止したすごく大きなチャンバーで最初は静止状態を保って、パッと噴き出すというのだとまた話は別だと思いますし、そういうブロアーとかコンプレッサーとか色々流してやっている時には、やはり装置によっても答えが違う。だから何が答えかと言ってもなかなか正解が一つですとは言えないのです。そういうリアルな問題というのは色々あるのではないかと思うのです。

会場：今の話とちょっとずれるのですが、それに関連して、要するに我々が今持っている EFD あるいは CFD をやれるリソース、予算であれ装置であれ人であれ、というのはいずれにしても限られているわけですよね。好きなだけ EFD をやっていい、あるいは好きなだけ CFD をやっていいという状況にはないわけですよね。そうすると仮にこれはどなたにお聞きしていいのか分からないのですが、例えば 20 回やっていいと言った時に 10 回 CFD やって 10 回 EFD をやって予測するのがいいのか。それとも 20 回全部リソース使って実験した方がいいのか。それとも 20 回全部 CFD やった方がいいのか。それとも EFD/CFD 融合の何らかの答えが出るのかと。どなたか分かりませんが、ぜひその話を聞きたいと思っていまして。

吉田：今のご質問の主旨はお分かり頂けましたでしょうか。誰かこれについてまずご意見をお持ちの方いらっしゃいますでしょうか。

佐宗：2 回目の質問に答えてなかったところがあると思いますが、要するに効率の話だと思うのですが、これはやはりケースバイケースで、どういう問題であってそれに対して最終的に何をどこまで得なければいけないかということを、人間が頭で考えるということになるのではないかと思います。その辺が昼ごはんの大切さということです。

口石：今回は議題が不確かさをいかに減らせるかということで効率性を議論の対象にするつもりはなかったのですが、確かに融合の一つの目的として効率化というものがあると思います。今回の我々の世界で原因として考えてみて、例えば JAXA が今開発しているハイブリッド風洞では事前 CFD をやって風洞試験計画を見直す。そういった効率化は当然可能だと思うのです。

吉田：今のご質問だと、ある制約の中でいかに

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効率よくやるにはどういう手法かとすると、例えば企業で Tinoco さんとか越智さんとかはある制限を与えられた中で目的を達しろと言われたときにどうするかという質問と同じだと思うのですが、何かお考えありませんか。

Tinoco：一つ注意しなければならないのは、解の違いによってどれだけ差が出るか、もしくは解を求めるにおいてどの程度の違いが生じるのかということです。私のお見せした衝撃波の位置の例では風洞の細かい条件に非常に敏感です。CFD でそれを如何にシミュレーションするかを詳細に考える事はどの程度重要だったでしょうか。空気力を調べているのであれば結果は変わりません。なぜならば衝撃波は翼上である位置から別の位置に動いてまた元に戻りますので、この繰返しの中で抵抗は結果的に同じとなるからです。衝撃波の位置は動き回るのですが、ピッチングモーメントについてもほとんど変わりませんでした。

こうした視点から見れば、学問的にこれらの感度が何たるかを調べることは重要かもしれませんが、実用的にはそうではありません。マネージャが要求するものは製品を最も安く、早く製造するために必要な答えです。それ以上である必要はありません。リスクはなぜそのような答になるのかを理解できない事にあり、ひょっとして我々にはその理解を得るに十分なリソースがないかもしれません。理解するためのリソースがないのであれば少なくともそれが重要でないとか、それにより差異は生じないと確信できるようにしておくべきでしょう。それ自体もリスクですが。

越智：例えば、その問題について自分がどれくらいよく知っているとか、どれくらい解析で合いそうだとかいうことがまずあります。例えば飛行機で言うと、先程のハイスピードラインの設計、巡航の設計が 20 回あるのだったら、15 回か 16 回くらいは CFD で残り 4 回くらいが試験かなと思いますし、例えばそれがロースピードで且つ形が今までやったことがないようなものだとなかなか CFD というのは難しくて、やはり実験でやるというところだと思います。

会場：JAXA の渡辺重哉です。発言し遅れて話が戻ってしまうのですが、これはあくまでも私の意見ですが、航空機であれば基本的にフライトの特性を知りたいというのは設計者だけではなく、我々全てが同じ思いだと思うのです。ではそのフライトのデータがまずあるかというところと、フライトでどれだけ正確なデータが取れるかという問題があります。いつも私は分からなくなるのですが、ボーイングとかエアバスのプレゼンテーションで予測値とフライトデータで揚力係数とかポーラーカーブなんかがよく合ったと言うのですが、エンジンの排気の補正をどうするかとかフライトでの飛行条件がどのくらい正確にわかったかとかを考えると、Tinoco さんのお話にもありましたが、両者の差が本当に正しかったのかどうかは十分に分からないのではないかと思っています。そうであればまず条件がより正確に分かる環境は何かと言うと、風洞だろうと思っています。もちろん風洞にも色々な uncertainty がありますがフライトに比べれば圧倒的に小さい誤差なので、まずはそこで実験と合うようにするというのが CFD をより良くする一つの方法ではないかと思っています。

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風洞においてもレイノルズ数はそれなりには変えられるので、それによって CFD でレイノルズ数効果を予測できるかをある程度は見ることはでき、まずはそこがファーストステップではないでしょうか。先程越智さんがおっしゃいましたが、まずはそこがマッチするということが一つの出発点になるのではないかと思っています。あとは高レイノルズ数風洞として ETW とか NTF とかがありますので、そういうのも活用しながら CFD をより鍛えていくとよいのではないかと思います。

私は実験が専門なのですが、実験屋は CFD に過剰な幻想を持っているからかも知れませんが、こう考えています。JAXA では PSP とか PIV とかを用いた面や空間の計測をやっていますが、実験というのは測れたところは計測誤差はあるものの、それなりに信頼性があります。ただ測れないところが出てくるのです。そうすると CFD の有効性について実感が沸きます。設計にこのような計測データを使われる方がこのような測れなかったところをどうやって埋めるかが物凄く難しいとおっしゃっていて、その通りだと思います。その解決策として実験データを境界条件として CFD を使って穴埋めするという考え方があるのですが、これもなかなか難しいとすると CFD であれば全状態量を全空間で計算出来るので、究極では CFD が信頼性のある予測ツールとして使えるようになれば設計上は物凄く有利だというふうに思っています。そうするとまずは実験レベルで CFD の信頼性をちゃんと確認できるようなプラットフォームを作ると、それが将来的にはフライトにも繋がっていくのではないかというのが私の考えているところです。

吉田：今のは先程の会場からの御質問への回答ということですか。ありがとうございます。会場の方から他に何かありますでしょうか。

会場：今のご意見に関連するのですが、CFD にとっては風試のレイノルズ数で結果を合わせろというのが非常に難しい。というのは模型スケールのレイノルズ数で考えると遷移が非常にセンシティブになってきて、例えばラフネスの位置をちょっと変えるだけでも実際試験では性能が大きく変わってしまう。そういった遷移位置が不確かな状態の中で CFD を合わせてというのがかなり難しい。むしろ CFD にとっては高レイノルズ数で遷移が固定されているという状態の方が合わせやすいというような現状があることも考慮して頂きたいと思います。

会場：今回のタイトルで EFD は風洞試験のことだと言われているのだけれども、飛行試験のことを言われるのは Tinoco さんだけです。飛行試験の結果がなくて、風洞試験と計算機だけで世の中閉じようとするのがおかしい。さっきから話題になっている衝撃波の位置なんていうのは境界線の厚さによって変わってくるわけですし、風洞の乱れにもよるでしょう。そういう敏感な要素がかなりあるはずで、それを飛行試験と風洞との対応を除いて、風洞とコンピュータだけでやるのはおかしいのではないでしょうか。

Tinoco：私もそうだと思います。もっと飛行試験が必要だと思います。飛行試験から得る詳細が必要です。ボーイングでは飛行試験はサイズの影響で非常に高価なこともあり、もっぱらの興味は機体強度と安定性・操縦性能を証明することです。会社は CFD や EFD を向上させるための境界層測定などに興味はありません。私達はいつでも「抵抗の少ないより良い翼を設計しろ」といった風に命じられているのですが、現象の詳細を知らなければそれを行うのは難しいのです。

では我々がやるべきことは何なのか。何かはできるのです。3 つの違うコードを走らせれば翼の後縁で起こることの詳細について 3 つの違う結果が出ます。でも風洞試験では模型のサイズ故に翼

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の後縁で何かを測るのは非常に困難です。飛行試験をすれば多分出来るのですが､誰もやりません。NASA をその気にさせようとしましたが、NASA には航空関連の予算がこれ以上ありません。JAXA でできるのであれば、何か共同でやれるかもしれません。最終的に私達がしたいのはよりよい飛行機を作ることで、そのためにはもっと理解が必要なのですから共同作業は良いことでしょう。CFD と風洞試験はその為の 2 つの通り道です。3 番目は飛行試験です。もっと詳細な情報を取れるようになる必要があるし、それらの情報には意味があるはずです。なぜ違いが生じるのか理解しなければならないが、よく分かっていない。ある程度は分かっていますが。まあ抵抗に関しては簡単ですね。抵抗が大きければエンジン会社のせいだと言えますから（笑)。エンジンが燃料を燃やしすぎるからで飛行機の抵抗ではないよと（笑)。でもエンジン会社は、違う違う、飛行機の抵抗が大きすぎるんだって言うでしょう（笑)。どちらも証明するのが難しいのですが。

吉田：やはり実フライトとの差をどう詰めるかというところが、そこにある不確かさをどうするかというところが議論になっていると思います。ひょっとしたらそれだけではないものもあるのではないかというので、先程冒頭で口石の方がそもそも不確かさは何かという定義の話をしたので、後ほどどうやったら減らすかという議論にいきたいのですが、その前にもう一度不確かさとは今議論しているようなことで、皆さんが考える方向で良いか。あるいはこういうのもあるのではないかということもあればもう少し議論したいのですが、何かそういうご意見などありますでしょうか。

会場：真の値が欲しいと思う時は模型の真の値が欲しいとか風洞の中で真の値が欲しいとかそういう話ではなくて、実機の真の値が欲しいという事ではないかと思うのです。先程から精度の話が出ていますが、1 カウントとか 0.1 カウントか、我々実機を扱っているものからするととんでもない。そんなもの測りようがない。もともとそんな高い精度のものを要求する必要はないのではないかと思うのです。要するに、相手は実機だと我々は思っているのです。学会で発表する分には風洞試験とコンピュータだけで話が済むかもしれませんが、実用的には本当の飛行機に対して風洞試験やコンピュータがどういう答えを出してくれるか。真に近いものを出してくれるかということになるので、0.1 カウントなんてことまで考えているとしたら、ちょっと話がおかしい様な気がしているのです。

口石：0.1 カウントは大げさだったかもしれませんが、基本的に風洞試験として最も確からしい値を出して、それが実用上どう役立てるのかが大切だと思うのです。先程会場からもコメントがありましたが、まずは風洞試験として正しい値を模索するのが我々のファーストステップなのではないでしょうか。それが分かった上で、さらにそこから実飛行条件を予測するためにはどうすればよいかという 2 つのステップでやっていかなければ、いきなり風洞試験から実飛行条件のデータを出すということは基本的に不可能なので、予測には段階があるのだと思います。あくまで風洞試験として正しい測定が出来ていることを保証するのが

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我々の最初のミッションだと思いますので、それが出来た上でさらにそれを実飛行に繋げる為にはどういったステップでやっていけばいいのかということ。その中にEFD/CFD融合のようなテクノロジーが入っていける余地があるのではないかというふうに考えております。フライトデータについてもMRJという飛行機が出来つつありますし、日本でもこれから必要になってくるのだと思います。

佐宗：今までCFDというのが、要するに風洞というか理想的な一様流での状態での答えを出すという役割だったと思うのですが、そういう位置づけで今議論が進んでいると思うのです。本来はフライトを実際にしなくても数値計算でフライトの、例えばエンジンのインテグレーションやレイノルズ数効果もそうですが、そういうことが出来るようになるというのがCFDの本来の果たすべき役割じゃないかと思うのです。現状の技術レベルの話ではなくて数値計算だから出来ること。だからもう少しCFDが役に立つようになる為にはフライトの時のシミュレーションが出来るようになるというところまでいくべきなんじゃないかと思うのですが、どうでしょうか。例えばちょっと話が違いますが、今私が関わっている宇宙推進でイオンスラスターの流れをシミュレーションしようというところはわりとやっていて、それもまだ片付いている話ではないのですが寿命予測を数値計算でやろうと。流れはそこそこ解けた。合わないこともあるけれども、ある程度それらしい答えが計算できるようになってきたと。今度はイオンスラスターだったらグリッドにどれだけのフラックスの、どれだけのエネルギーのイオンがぶつかってきて、どれだけ消耗するか。それを数値的にやろうと。そうすると数値シミュレーションで良いことは、リアルタイムよりももっと先取りして寿命予測ができる。そんなようなことも今されていて、そういう意味ではCFDがこれから何をしていくかということで、一部はもちろんFlight DynamicsとFluid DynamicsのダブルのCFDをやられているところもあるようですが、本来は数値計算がそういうフライトに代わるようなフライトの実験の回数を減らせるようなものになっていくべきではないかと個人的には思います。

越智：メーカーの立場から言うと、何度も言っていますがフライトのデータを予測するというのが一番なのですが、じゃあそれを一体誰がやるのかという話が一方でありまして、それまでをJAXAさんにお願いするのか。そこはやはりメーカーの仕事なのかというところがあると思います。基本的にはフライトと合わせるというのは機体によって変わってくる面もあり、ユニバーサルにどんな機体でも飛行の値を見積もるというのは遠い将来の話だと思うので、近未来のターゲットという意味では風洞試験とCFDを合わせるというのはそれほど悪いことではないかと思います。但し会場からの発言でもあったように、CFDにとって風洞試験の条件というのは逆に難しい面もあるので、最終的には実機を推定するということを忘れずに頭に置きつつ、まずは風洞試験とCFDとを比較していくことでお互いの不確かさを減らしていくというのがアプローチとしては間違っていないのかと思います。

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Tinoco：いかなる航空機開発プログラムにおいても、実飛行特性の予測に対しては非常に慎重になる必要があります。そのような特性が燃料消費についてどうなるかといったことを航空会社に対して小さなパーセンテージで保証しなくてはいけない。一旦空に飛ばしたらすぐに安全性を FAA に対して示す必要がある事も忘れてはいけない訳で、このためには航空機に微調整が必要になります。毎回の事です。かつて飛ばしたどの飛行機でもある程度の調整をしなければなりませんでした。そこで小さな調整で済ましたいわけです。そうでないと会社がつぶれかねない。多くの例がありますが、アメリカでは飛行予測ができなくていくつかの会社が航空機ビジネスから撤退しました。風洞や CFD はあくまでこれら飛行予測ツールの一部に過ぎません。ボーイングではこれまでの歴史、私達が開発してきたこれまでの航空機の経験を大いに頼りにしています。作業をどう進めるかについての多くの情報があるのです。過去の風洞試験や CFD を新しい航空機のものと比較して、飛行性能がどうなるかについて最善の予測を立てます。こうした予測を過去の知見無しで盲目的に行うのは不可能でないとしても大変難しい事でしょう。これが飛行試験なしに大型航空機ビジネスに参入することが難しい理由の一つだと思います。つまり、風洞試験のみ CFD のみでは完全な回答が得られないであろう故に、これまでの知見の蓄積が今日でも非常に大きな比重を占めているのです。ですから風洞試験と CFD の 2 つを使って知見を向上させ、その向上された知識を通じて不確かさを減らしていくことを目指しているわけです。

Meade：Dr. Tinoco のおっしゃる事の繰り返しになってしまいますが、基本的に EFD と CFD というのはツールに過ぎず、我々は製品を作ろうとしているわけです。単純機械的に作るだけであれば誰もこんな話はしません。何人かがおっしゃった通り、非常に困難な問題に対して絶対的な真実ではなく許容できる真実を得ようとしているわけです。製品を飛ばす事を可能にする真実を、風洞試験であれ縮小模型の飛行試験であれ CFD であれ、試行錯誤で得ようとしているわけです。分かりにくくなるのはその 3 つの間に相互作用があるからだと思います。究極的には飛行機を飛ばしたい。そのために設計で未知の要素を可能な限り減らしたい。EFD では優れた装置と経験で真実に近づいていると信じている。しかしながら測定できるものはほんのわずかです。CFD は素晴らしいツールですが問題もある。でも少なくとも実験での空白を埋めて実験を補助することができる。実験結果を保証するか、あるいは将来の実験のガイドとして空白を埋めるために使うことができるわけです。繰り返しますがいずれも単に製品を作るためのツールに過ぎないのです。しかしこうした EFD と CFD の融合により空白を埋めて、製品を設計するための許容できる真実により近づこうとする過程の中で不確かさを減らすことが可能になると思います。

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吉田：色々意見が出ましてこの話をもっと詰めたい気もするのですが、今の話に限定しまして、例えば実際のフライト時の状況を知る為に EFD と CFD を有効に活用するのであれば、どういうふうに有効に活用する方法があるか。つまり不確かさをいかに減らしていくかという手法です。今回このプロジェクトで目指すものもそうですし、その点についての具体的にこういうのをしたらどうかとか、あるいはこういうのを日本全体でやろうとか、あるいは JAXA にやってくれとか、そういう要望等ありましたら遠慮なく言って頂きたいのですが、その点に関するご意見などありませんでしょうか。如何にお互いが助け合うかという重要性はかなり議論できたような気がするのですが、では具体的にどういうふうにしたら一歩前進、つまり一緒に食事する回数をいかに増やすかという方向の議論だと思うのですが、何かありませんでしょうか。

佐宗：良いアイデアがあるわけではないのですが、東北大学の流体融合センターがやられていることがかなりデータ同化に近くて、要するに上流から素性がよく分かっていない流れがきた時に、例えば円柱を置いてその後流はどうなるかと。それを 1 点 2 点の圧力や速度情報だけでフィードバックをかけて、上流の流れを予知しようという試みです。そういう試みは航空に特化した話ではないのですが、その辺りはこのプログラムを見ますと、明日のデータ同化の話も同じだと思うのですが、そういうところは一つはやはりあってもいいかなと。ただ風洞試験にリアルタイムで、風洞が動いている間にリアルタイムの情報が来てもそれが何の意味をなすかということがあると思うのですが、目指しているところは数値計算と実験のターンアラウンドをもう少し短くするということが一つ、誰もが一週間や一ヶ月単位でやっていては駄目だというところがあると思うのです。ターンアラウンドを短くするという意味で、僕が知っている限りでは東北大のグループがやられていることというのは繋がるのではないかと思います。

吉田：ありがとうございます。具体的な解というのは思いつけば皆やっているわけですからなかなか無いとは思いますが、そういうのを思考して少しでもアイデアを出してやっていくというのが重要だと思いまして、今の先生のお話はありがたいと思います。他に何かそういうアイデア、何でも結構ですが、あるいはこうしたらよいのではないかというコメントなどありましたらお願いします。

会場：今の佐宗先生のお話に関連してですが、データ同化の手法というのはかなり今色々発展していて、我々も何か使えるものがあるんじゃないかということで、試験的に何かリデュースドモデルに適応したりということをやっていこうと思っています。それで色々調べていこうと。ただ個人的なのですが、航空宇宙に非常に特異な問題は、例えば東北大でやっているカルマン渦のシミュレーションというのは実験自体がかなり知りたい真実に近いわけです。我々の知りたいことに近いそれを計算との比較対象としている。ところが航空宇宙の場合は風洞試験と計算を比較させる。風洞試験も実は物理現象として我々の知りたいことではあるのですが、そこからもう一段ありまして、我々が本当に知りたいのはリアルフライトである。そうすると風洞試験と数値計算というのをまず比較する。これは意味があるのでしょうけど、それをデータ同化とか使って近づけることは出来るのではないかという期待があるわけです。で、それをやった後に今度は風洞試験もしくはその風洞試験にかなり合わせたというか、お互い協力してかなり良い結果が出せるようになった数値計算とリアルフライトのところを何とかしないといけない。いわゆるリアルフライトと風洞試験もしくは数値

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計算との差分というのを考えなくてはいけないわけで、それが非常にここでの航空宇宙での問題の特異性となっているのではないかと思います。そのようなところにどのように貢献できるか、EFD/CFD 融合の観点から何かこのディスカッションの場で方向性を示して頂けるといいなと思うのですが、いかがでしょうか。非常にプリミティブに考えているのは、例えば数値計算だとその差分が非常に出しやすいのではないか。実験より出しやすいのだったら、その場合は数値計算がリアルフライトを計算すると案外楽かもしれないのです。境界条件とかがまだ複雑にはならないですから。ところが風洞試験だと非常に複雑な様相が境界条件などに入ってくる。そこで数値計算をしっかり出来ればその差で風洞試験とリアルフライトの差が取れるとかいうことがあるのではないかというプリミティブな期待をしてしまいます。その辺り実際の会社でやられてご存知な方からお知恵を貸して頂きたいと思うのですが、いかがでしょうか。

吉田：今の質問になかなか明確な回答は難しいと思いますが、ありますでしょうか。

越智：実機というのは風洞試験模型と CFD モデルとは全然違うのですよ。やはり実機の予測というのはまた別次元の話で、巡航だと空力弾性が違うとかパネルの表面粗さとかギャップとか、後は色んなところに小さいアンテナがポツポツついていたりして、それが 1 個につきコンマ何カウント分の影響があったりとか、それでもまだやろうと思えば出来ない話ではないかと思うのですが、ロースピードになると本当に Tinoco さんが言われた通りで、形が分からないのです。どんな形で飛んでいるのか分からないのです。その中でそれを予測するというのは非常に難しくて、ちょっと経験則的な方法でやるという形にならざるを得ないというところで、システマチックにやるのはなかなか難しいのかと思っています。

会場：そうなりますと、リアルフライトが分からなければ意味がない。これは究極の目標なのですが、その前に風洞試験と数値計算というのを相互作用させて、少なくとも風洞で起こっている物理現象についてはきちんとつかめるようにしたいというのは、こういうプロジェクトを進めていく上で第一ステップになり得るということなのでしょうか。その辺りの方向性というのも、いきなりストレートフォーワードには行かないのでステップを切っていくと思うのですが、どのようにすればよいのかが知りたい点であるのですが。宜しくお願い致します。

Meade : EFD、CFD、飛行試験とステップを踏むことになるのではないでしょうか。実験からの情報は比較的限られているように思えます。その情報の空白を埋めるために CFD と融合できるでしょうし、その融合過程で CFD の感度や信頼性が分かります。実際、Dr. Tinoco もおっしゃった様に、CFD では格子や乱流モデルなど、多くの問題がありますから。ですからこの融合データを使って大きな不確かさのおこる部分が分かれば、多分それを修正して飛行試験に応用できるわけです。

さて、私の考えですが、飛行試験に行く前に改良されたモデルを採用して感度を調べる。例えば翼やアンテナの形状とか、そんな境界条件を変化させたらどうなるかとか、そしてそれらが飛行試験で計測可能な変数にどう影響するかとか。それで結果が真実に近いか否かも分かります。実施した計測が先ほど言った意味での境界条件の少々の変化の中に納まれば結果にある程度の自信が持てるでしょうし、はるかに外れた所にあれば風洞実験と CFD の所にまで立ち戻らなければならないと分かるでしょう。

Tinoco : 簡単な答えはないと思います。全てやって、やり続けるしかないわけです。飛行試験で

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データが取れたら比較できることもあるでしょう。飛行試験で 0.1 カウントの抵抗まで調べることはできないでしょう。というのはフライトデータは全てが統合されたもので、そこではエンジンも重要な要素になっているからです。しかし圧力の分布を見ることは可能でしょうし、そのためには機体の実形状を計測するか、もしくはある程度予測しておくことが必要になります。これら全てが意味を持つはずです。データを取り、統合して一つのストーリーを作ることができるはずです。もしも一つのストーリーに統合できなければ、何故と問わねばなりません。大方その理由は同じ質問をしていなかった、同じものを測定していなかったからです。風洞から CFD、飛行試験で条件が異なっているとか。最終的にはそれら 3 つで同じ質問をして同じ答えが出たら、大きな前進ということです。言うは易しですが。私達はそうすることから遠い場所にいる様に思いますが、多くの事でここは自信があるという所もあります。ですから私達は飛行機を飛ばすのです。また飛行機を飛ばした時、意外なことが必ず出るわけです。それが修正可能なちょっとした驚きであることを望んでいますが。

吉田：時間がそろそろ迫ってきたのですが、何かこういうことをやりましょうとか、このワークショップはまた来年もあると聞いておりますので、それに向けて今このプロジェクトがやっている EFD/CFD 融合の中のコンポーネントにするという提案でもいいですし、何かこういう事をもっとやって欲しいというご提案などありませんでしょうか。

会場：無理を承知でわがままなお願いをします。個人的には最終的に CFD で全て解けたらいいなと。設計もできたらいいなと思っております。今のところその為の検証データとして風洞試験があるのであれば、今欲しいのは実フライトの検証データということで JAXA には実フライトの、旅客機クラスのレイノルズ数で圧力分布であったり力であったり、そういうデータをぜひとも計測、公表して、日本中なり世界中なりの研究者が検証データとして使えるようなデータベースを揃えて頂きたいなと思います。

それは無理にしてもすぐ何が出来るかというと、風洞試験を正確に CFD で模擬できたら、恐らくその CFD のコードはかなりの部分で validatte なり verificate できる。とすると例えば遷音速風洞の中での全体を解いたようなことにも当然なる。昔見たことがあるのですが、風洞を丸ごと解いてしまうような、中に模型が入っている状態を CFD で解いて検証データとして揃えられないのかと。それは力だけではなく、圧力分布のようなものがワンセットあると、地方の大学の研究室でもそれを参考にして CFD のコードを役立てることが出来るかと思いますので、是非ともお願いしたいと思います。

吉田：ありがとうございました。飛行試験はなかなか難しいですが、後者の風洞を丸ごというのは多分試みはあるでしょうし、JAXA のプロジェクトでもスコープに入っているのですかね。

渡辺：コメントありがとうございます。JAXA に何かやれと言われる方がやらなくていいと言われるよりずっといいので有り難いのですが、フライトデータを予測するのはメーカーの仕事か JAXA の仕事かと切り分けるのではなくて、両方がやるというのがこれからではないかと私は思っています。というのは風洞試験だけやっていると風洞試験条件下での CFD と実験のことばかりを考えるようになってしまうので、フライトデータに JAXA も触れるようなことをしていかないとトータルに日本全体の力も上がらないのではないかというのが私の思いです。フライトデータは非常にセキュリティの高いデータで JAXA がメーカー

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からなかなかもらえないというところがあるのですが、もらえればそういうこともどんどんやっていきたいと思います。もちろんパブリックにオープンというのは難しいとは思うのですが、1 点目のご指摘への回答としては希望として私たちもそういうことをやりたいと思っているところです。

2 点目については、実際に我々も風洞壁とか支持の補正をやらない実験データと壁も支持もない CFD データを比較してしまっていることが未だにあるので、そういうことがないように壁と支持も含めた CFD が出来るように考えています。ただそれを検証する為の実験データも 6 分力だけでなくて、表面圧力の詳細な分布だとか空間の速度ベクトルとか、そういうものをセットにしたデータベースが必要だと考えています。今までデータベースというと実験だけというのが多かったですが、我々は実験と CFD と同じ条件のデータをセットにしてデータベース化したいと思っていますので、ご要望に応えられるのではないかと思っています。

Tinoco : 指摘しておきたいのですが、NASA は公開していますよ。第 4 回の Drag Prediction Workshop では common research model を使用する予定です。巡航形状でしたらウェブ上で公開されますので、ダウンロードは誰でもできます。また風洞試験は NTF で多分 5 月頃に行われることになっています。その後、同じ模型で Ames の 11 フィート遷音速風洞でも試験される予定です。少なくとも 2 つの試験が行われることになります。その模型は JAXA の遷音速風洞には大きすぎるかもしれませんが、NASA は模型製作の為に形状データを提供できると思います。それから飛行試験についてはボーイング 757 を買われたらよいのではないでしょうか (笑)。中古機だったらもうそんなに高くないでしょうし、うちの会社は割引しますので、いかがですか (笑)。

渡辺：これは将来どうなるか分からないのですが、希望としては MRJ が実際に飛んで TC も取った後には飛行試験が出来るような機体として JAXA も含めて維持できるといいなと思っているので、757 を使わなくてもよいかもしれないと思っております (笑)。

吉田：ありがとうございました。そろそろ時間ですが、最後にもう 1 言くらいこの機会ですので何かありますか？

会場：私は今 uncertainty に皆さん焦点を置き過ぎているのかなという気が多少します。これはまだまだ研究的な要素が非常に大きいところであって、フィジックスを混ぜた場合に上手くいくかどうか分からない。それよりも二人が一緒になるのだったら、一緒にいる時間を作るほうが大事なんじゃないかと。ですから、最初のターゲットとして、productivity とか efficiency というところにもう少し重点を置くのも悪くないのかという気がしています。

それから飛行試験に関して言うと、私はヨーロッパって非常に上手く今やっているなという気がします。High-Lift とかの計画を立てていて、レイノルズ数効果や空力弾性、支持干渉の効果、恐らく次はパワー風試やエンジン排気のシミュレーションの方に行くのだと思うのですが、そういうのを非常に綺麗に積み上げてきている。ぜひ MRJ もしくはボーイング 787 を利用して JAXA やメーカーの中でそういうものを共有できるようにしてもらいたいと思っています。

それからもう一つだけ、佐宗先生のアナロジーで言うと、やはり sensitivity が大事なのでしょうね。異なる二人が一緒にやっていく為には鈍感じゃ駄目だということじゃないかという気がします。

口石：おっしゃる通り uncertainty に偏りすぎたという点はあるのですが、今回は議論をシャープにする為にあえて uncertainty で限定してテー

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マを組んでみたのです。このワークショップは来年以降も続けるつもりなのですが、次回はパネルディスカッションのテーマが既に決まっていて、“ Can EFD/CFD integration maximize productivity?”、そういう形で 5 年くらいは持つかなと（笑）。ということで次回もぜひご参加下さい。

吉田：では時間もそろそろ来ましたので、これで終了させて頂きます。ここに集まっていらっしゃる方は EFD がご専門の方も CFD がご専門の方もいますので、まさに懇親会で together をというのが今日の唯一の解（会）ではないかと思うので宜しくお願いします。どうもありがとうございました（拍手）。

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