第3回EFD/CFD融合ワークショップ
The 3rd Workshop on Integration of EFD and CFD

Xaero

TOHOKU UNIVERSITY

「EFDと飛行シミュレーション - 次世代動的風洞実験法の開発に向けて」

EFD and Flight Simulation

Towards the Development of the Next-Generation Dynamic Wind-Tunnel Testing

浅井圭介，永井大樹，近野　敦
Keisuke Asai, Hiroki Nagai, Atsushi Konno
Tohoku University
Sendai, Japan

Akihabara Convention Hall, Tokyo, Japan
January 25, 2010

TOHOKU UNIVERSITY

Contents

- Background
- Role of EFD in Flight Simulation
- Dynamic Wind-Tunnel Testing (DWT)
  - Fundamental
  - Current Techniques（Forced Oscillation, Free-Flight, etc)
- Evolution of DWT
  - New requirements and new technologies
- Future of DWT
  - Research Plan at Tohoku University

Asai, Nagai, Konno (2010)

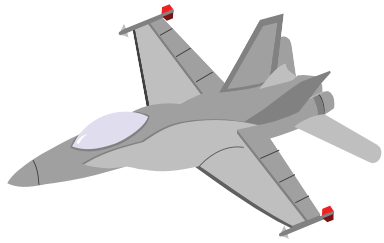
Aircraft Equations of Motion

● Translation (3 degrees of freedom)

$$X - mg\sin\Theta = m(\dot{U} + QW - RV)$$

$$Y + mg\cos\Theta\cdot\sin\Phi = m(\dot{V} + RU - PW)$$

$$Z + mg\cos\Theta\cdot\cos\Phi = m(\dot{W} + PV - QU)$$



● Rotation (3 degrees of freedom)

$$L = I_x\dot{P} - I_{zx}(\dot{R} + PQ) - QR(I_y - I_z)$$

$$M = I_y\dot{Q} - I_{zx}(R^2 - P^2) - RP(I_z - I_x)$$

$$L = I_z\dot{R} - I_{zx}(\dot{P} - QR) - PQ(I_x - I_y)$$

Aerodynamic Force (*X, Y, Z*)
Moment (*L, M, N*)
Angular velocity (*P, Q, R*)
Euler angular velocity (φ, θ, ψ)
Moment of inertia (*Ix, Izx,* ・・・)

Exhibits a strong **nonlinearlity**

1) Computer simulation: solve these nonlinear equations numerically
2) Analytical approach
   - Linearize the EoM (**small disturbance**) $U = u_0 + u, P = p_0 + p, \Theta = \theta_0 + \theta, \ldots$
   - Express Aerodynamic force terms with other parameters (**Bryan's method**)

→ Enable us to investigate the "**modes**" of aircraft motion

Asai, Nagai, Konno (2010)

Aerodynamic Force and Moment Representation Concept of "Stability Derivative"

Aerodynamic forces and moments can be expressed by means of a Taylor series expansion of the perturbation variables (velocities, angular velocities, accelerations, etc.) about the reference equilibrium condition.

$$\Delta X = \frac{\partial X}{\partial u}u + \frac{\partial X}{\partial \dot{u}}\dot{u} + \frac{\partial X}{\partial v}v + \frac{\partial X}{\partial \dot{v}}\dot{v} + \ldots + \frac{\partial X}{\partial r}r + \frac{\partial X}{\partial \dot{r}}\dot{r}$$

$$= X_u u + X_{\dot{u}}\dot{u} + \ldots + X_r r + X_{\dot{r}}\dot{r}$$

George H. Bryan (1864-1928)

The term, X_u … , is called the "Stability Derivative" and is evaluated at the reference flight condition.

Retain only the linear terms and also neglects some first-order terms that have small contributions to aircraft motion

1) Motion in the symmetric plane → Y, L, N=0 and their derivatives=0
2) Lateral motion → neglect derivatives with respect to forces and moments in the symmetric plane (X, Z, M)
3) Neglect derivatives with respect to accelerations except $M_{\dot{v}}$ and $Z_{\dot{v}}$
4) Neglect other terms (e.g. Xq) that are expected to be small from the physical viewpoint

Dynamic stability

Longitudinal motions

- Short-period mode (several seconds)
- long-period or Phugoid mode (order of 30 or more seconds)

… gradual interchange of potential and kinetic energy about the equilibrium altitude and airspeed

Lateral motions

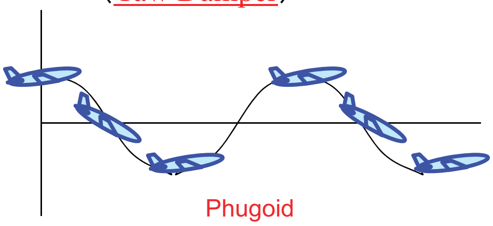
- Spiral mode

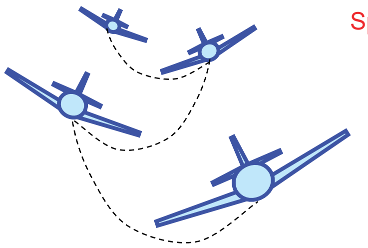
… Directional stability (Cnβ) too large, while lateral stability (Clβ) inadequate → SPIN

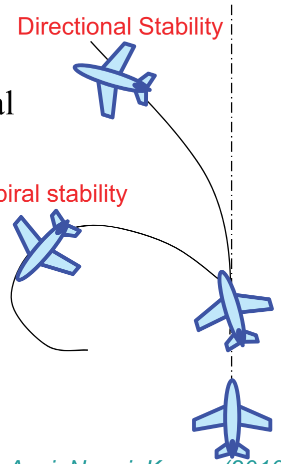
- Rolling mode
- Dutch Roll mode

… Lateral stability (Clβ) too large, compared with directional stability (Cnβ) → degrades pilots' and passengers' comfort

→ stability augmentation system (Yaw Damper)







Asai, Nagai, Konno (2010)

USAF Digital **DATCOM**

Computer program to calculate the static stability, control and dynamic derivative characteristics of fixed-wing aircraft, based on an input file containing a geometric description of an aircraft.

Ref: *"the USAF Stability and Control Datcom" AFFDL-TR-79-3032（1979）*

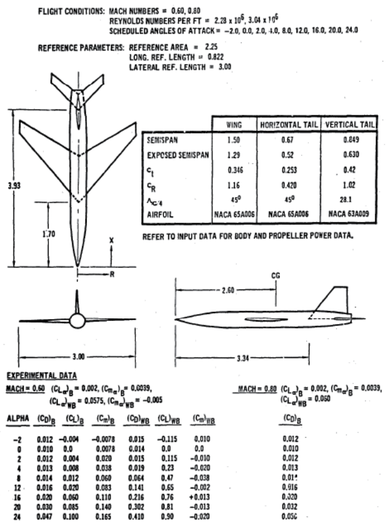


FIGURE 31 EXAMPLE PROBLEM 3 DATA

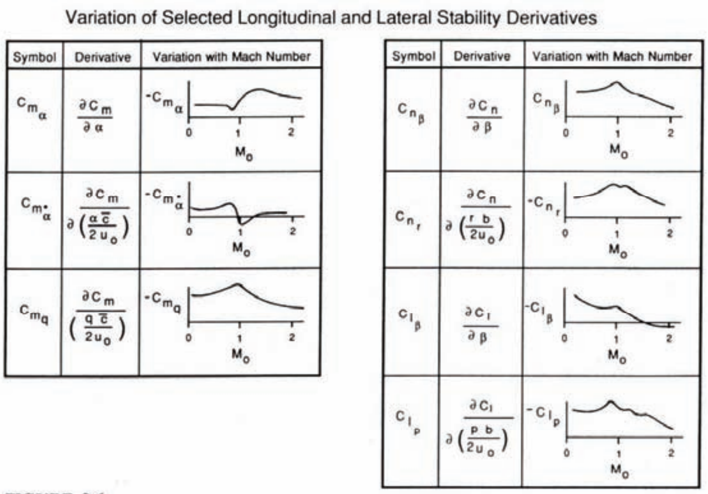


FIGURE 3.6
Variation of selected longitudinal and lateral derivatives with Mach number.

http://en.wikipedia.org/wiki/USAF_Digital_DATCOM

Empirical method

Source : http://www.pdas.com/datcom.htm

Dynamic Wind-Tunnel Testing (DWT)

Objectives:

1) Dynamic derivative
2) Spin Characteristics
3) Flight trajectory (e.g. store separation)
4) Tuning control laws (active control test)

写真引用：BOEING NASA

- **Fixed**
  Free oscillation
  Forced oscillation

- **Semi-free**
  Cable mount
  Real time Simulation
  Captive Trajectory

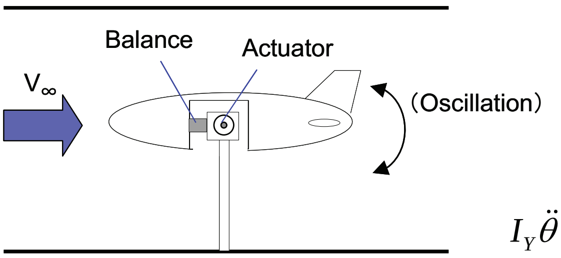
- **Free**
  Spin tunnel
  Free flight
  Ballistic Range

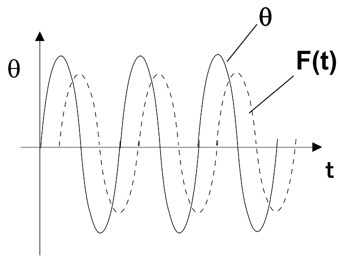
- **Flight Test**
  Scaled model
  Drop test

Asai, Nagai, Konno (2010)

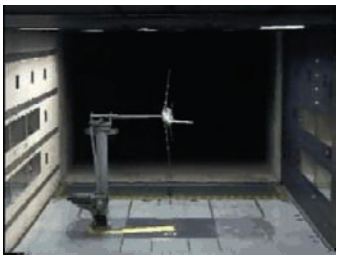
Forced Oscillation Testing

Forcing a model to perform a single-degree-of-freedom angular oscillation about its pitch, yow, and roll axes by means of an electric or hydraulic moter and the output of the balance inserted in the model is processed to measure dynamic derivatives.

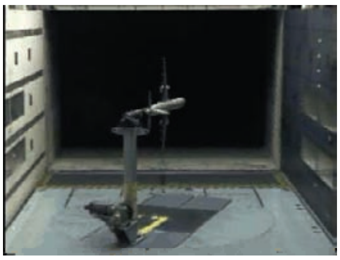




$$I_Y\ddot{\theta}+(C_{Ya}+C_{Yt})\dot{\theta}+(C_{Ka}+C_{Kt})\theta=M_Y$$



Pitch

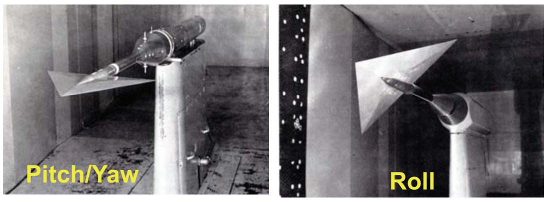


Roll

Yaw

写真引用：NASA *NASA Langley Research Center*

Forced Oscillation Testing at JAXA



Kobashi, et al, NAL TR-196 (1970)

Miwa and Ueno, JAXA-RR-03-021 (2004)

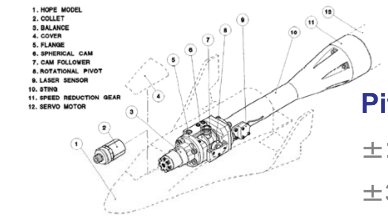


図1 Pitch/Yaw加振装置構成図

Pitch/Yaw

±1deg@15.0Hz

±3deg@8.7Hz

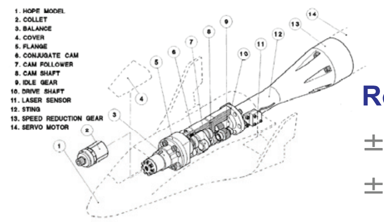


図2 Roll加振装置構成図

Roll

±1deg@30.0Hz

±3deg@17.3Hz

Length:1085mm, **Weight: 9.395kg**
CFRP (skin) + Aluminum Alloy (frame)

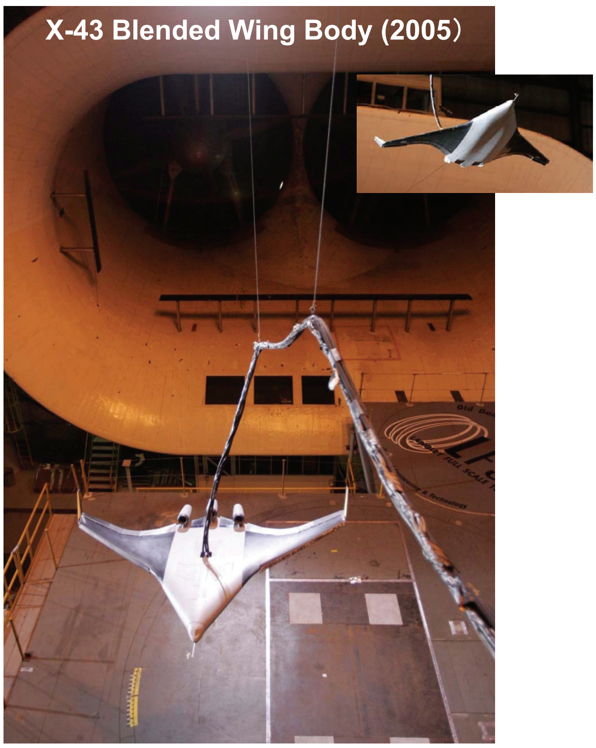
表6 航技研2m遷音速風洞において求める動安定微係数

Apparatus	Primary Oscillation	Damping Derivatives	Cross Derivatives
Pitch/Yaw	Pitching Oscillation	$C_{mq} + C_{m\dot{\alpha}}$	
Pitch/Yaw	Yawing Oscillation	$C_{nr} - C_{n\dot{\beta}} \cos\alpha$	$C_{lr} - C_{l\dot{\beta}} \cos\alpha$
Roll	Rolling Oscillation	$C_{lp} + C_{l\dot{\beta}} \sin\alpha$	$C_{np} + C_{n\dot{\beta}} \sin\alpha$

Free Flight (NASA 30ftx60ft)

http://oea.larc.nasa.gov/PAIS/Partners/graphics/X_31/fig08.jpg

http://oea.larc.nasa.gov/PAIS/Partners/graphics/FA_18/fig07.jpg



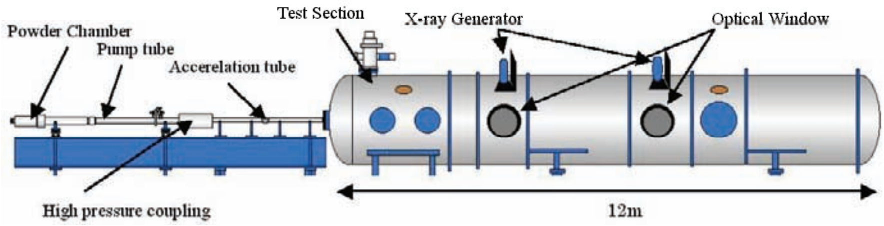
http://www.nasa.gov/images/content/137810main_blended_wing_hires.jpg

Ballistic Range

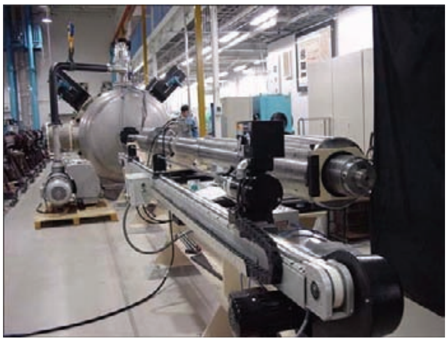
Institute of Fluid Science, Tohoku University

Operational Mode

1) Single-stage gas gun mode : ϕ15 & ϕ 5, max 0.7km/s
2) Single-stage powder gun mode : ϕ 15 & ϕ 51, max 2.4km/s
3) Two-stage light gas gun mode : ϕ 15, max 7-8km/s



Toyoda et al
(AIAA-2010-873)



Specification		
Pump tube	i.d. :	51 mm
	length :	3.4 m
Launch tube	i.d. :	15 mm
	length :	3 m
Test section	i.d. :	1.66 m
	length :	12 m

Asai, Nagai, Konno (2010)

Dynamically-Scaled WT Model

Dynamically Scaling

In order for a subscale body to appropriately represent the motion and response of a full scale body, the test vehicle is required to be dynamically scaled. This means that not only is the test vehicle scaled dimensionally, but also in weight, inertias, control, and actuation systems.

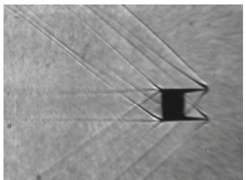
Scale Factors for Dynamic Models

Quantity	Scale Factor
Linear dimension	N
Relative density ($M/\rho L^3$)	1
Froude number $V/(Lg)^{0.5}$	1
Weight	N^3/σ
Moment of inertia	N^5/σ
Linear velocity	$N^{0.5}$
Linear acceleration	1
Angular velocity	$N^{-0.5}$
Time	$N^{0.5}$

N: model-to-airplane scale ratio
σ: the ratio of air density at airplane altitude and that at the model altitude

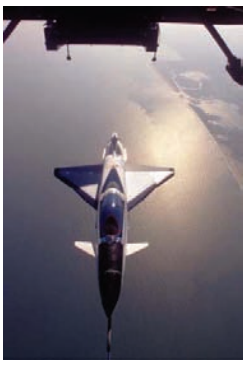
Gainer and Hoffman, "Summary of Transformation Equations and Equations of Motion Used in Free-Flight and Wind Tunnel Data Reduction and Analysis," NASA SP-3070, 1972.

Ref: *Croom. Et al;"Dynamic Model Testing of the X-31 Configuration for High Angle-of-Attack Flight Dynamics Research", AIAA-1993-3674.*



Source: 東北大

27%-Scale Drop Model



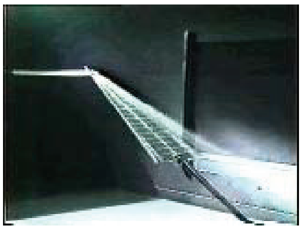
Source: NASA

Asai, Nagai, Konno (2010)

Nonlinear Flight Dynamics - Wing Rock

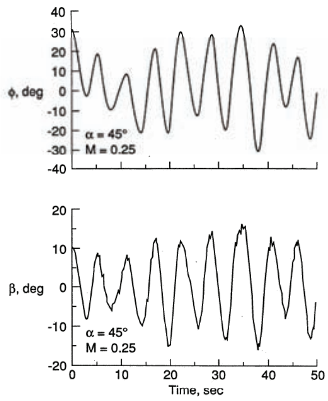
A ***wing rock*** is a **self-excited rolling oscillation** of a delta wing that is induced by unsteady aerodynamic forces.

- -Dynamics of leading-edge separation vortices
- -Vortex breakdown (bursting)
- -Hysteresis (energy dissipation or addition)



R.C. Nelson (Notre Dame)

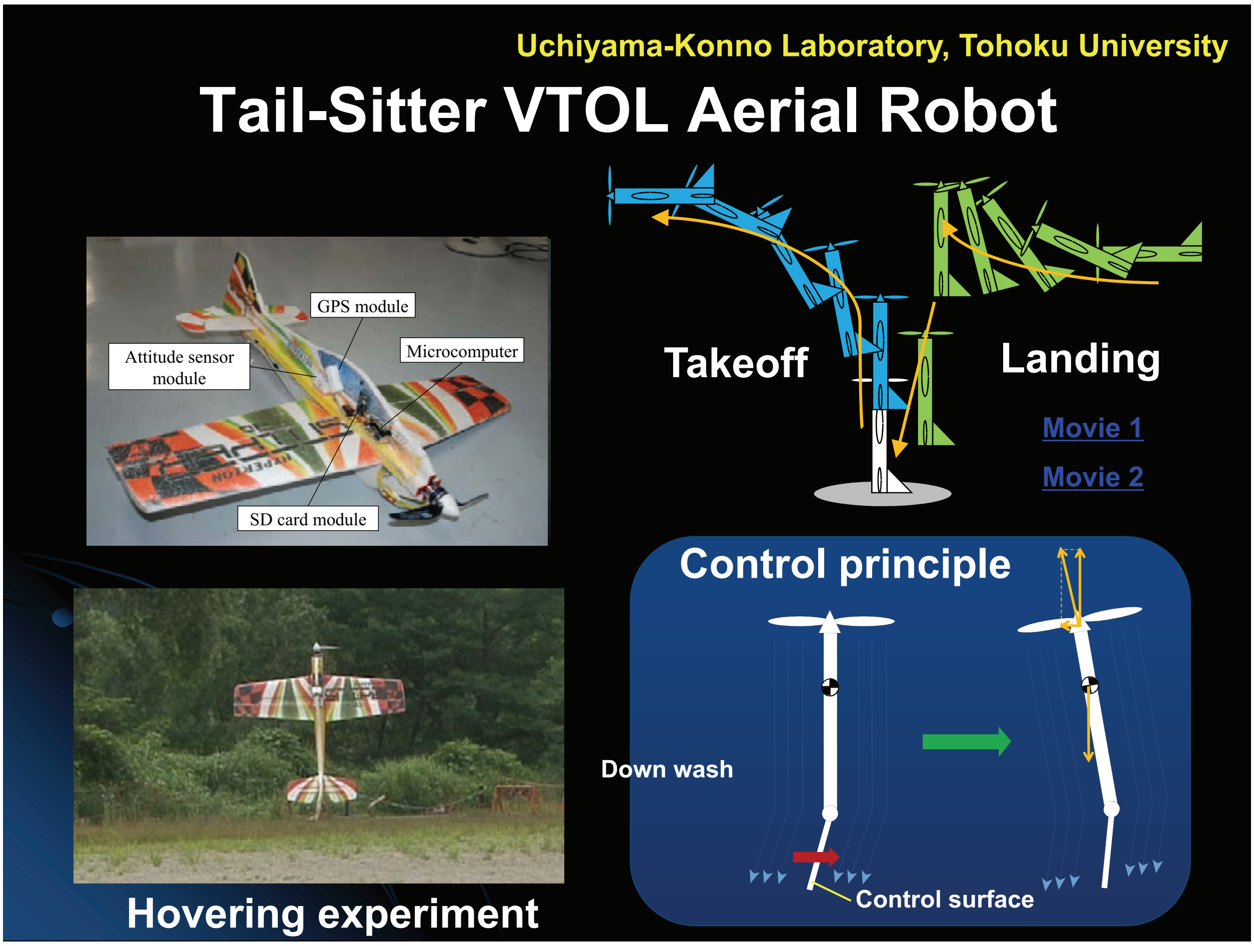
F-18 High Alpha Research Vehicle (HARV)



Quest, T., et al, AIAA-91-3267 (1991)

Becomes closely integrated with flight control system
→ Requires extensive ground and flight simulation

Asai, Nagai, Konno (2010)

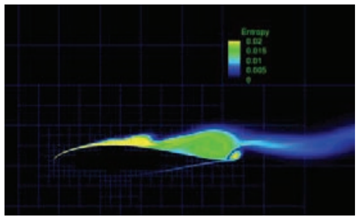


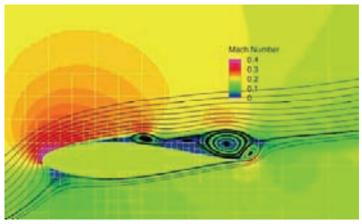
Progress in Unsteady CFD

- **Computation of largely separated flow**
  Unsteady Reynolds-averaged Navier Stokes (**URANS**)
  Large Eddy Simulation (**LES**)
  Detached Eddy Simulation (**DES**)
- **Structured/Unstructured grid**
  Treatment of moving boundaries and objects
- **Rapid progress in computer performance**

➡ **"Digital Flight Dynamics"** **Prof. Nakahashi**
The last aeronautical CFD grand challenge!

RANS Simulation around NACA 633-018 Airfoil using Building-Cube Method

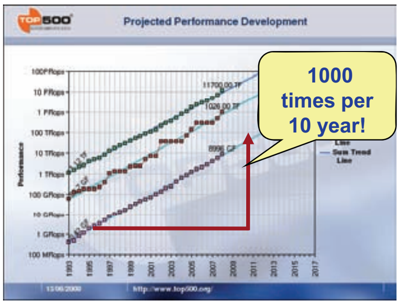




Nishimoto et al, AIAA-2010-0710

Earth Simulator (JAMSTEC)

Supercomputers TOP500 (June 2008)

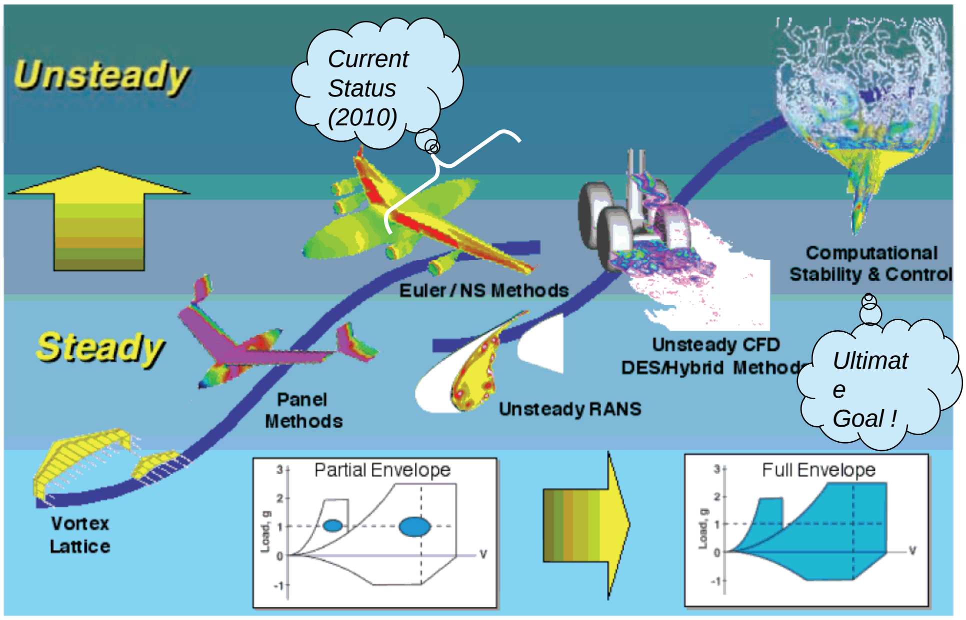


Asai, Nagai, Konno (2010)

Digital Flight Dynamics

- NASA Langley Research Center -

An ability to simulate in a computer a flight maneuver satisfying the governing flow equations, the aircraft aeroelastic characteristics, the 6-DOF equations, the flight control system, and the propulsion system.



AIAA 2007-6573, J. J. Chung, et al. "Development and Assessment of CFD Methods for Integrated Simulation of Air Vehicle Stability and Control"

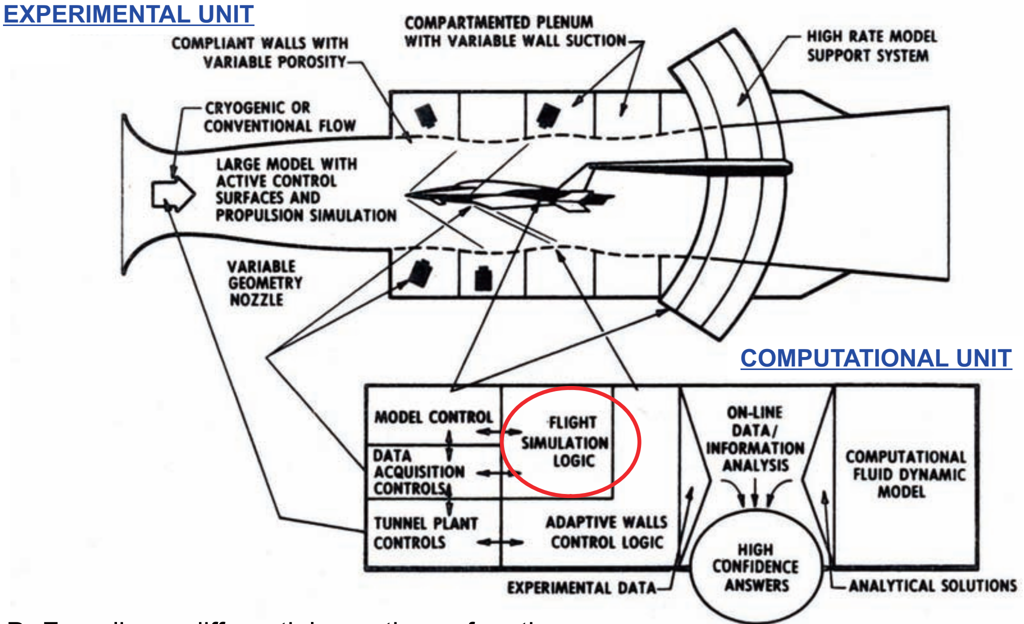
"THE ROLE OF COMPUTERS IN AERODYNAMIC TESTING"（1980）

Computers and fluids vol.8, pp.71-99
"THE ROLE OF COMPUTERS IN AERODYNAMIC TESTING"
Jack D. Whitfield, Samuel R.Pate, William F. Kimzey and David L. Whitfield
Sverdrup/ ARO,Inc., AEDC Division, Arnold Air Force Station, TN 37389, U.S.A.
(Received 13 April 1979)

1.Introduction
2.Critical areas in today's experimental aerodynamic facilities
Data accuracies.
Operational efficiency.
Simulation.
1.The current role of the computer in experimental aerodynamic testing
(1)Captive trajectory system testing.
(2)Self-optimizing, flexible wing testing.
(3)Simulation of flight maneuvers.
(4)Constant aerodynamic parameter testing.
(5)Flow-field measurements.
2.Current uses of computational fluid dynamics(CFD) in aerodynamic testing facilities
3.The future role of computational fluid dynamics in aerodynamic testing
5-1 Corrections for model support system interferences
5-2 Application of CFD to change our philosophy of facility operations
5-3 Development of adaptive walls for transonic wind tunnels
5-4 Computer technology applied to free-jet engine-airframe integration testing
6. Concluding remarks
References

CONCEPT OF ADVANCED TECHNOLOGY WT FACILITY

Merging of WT and Computer (AEDC (1980))



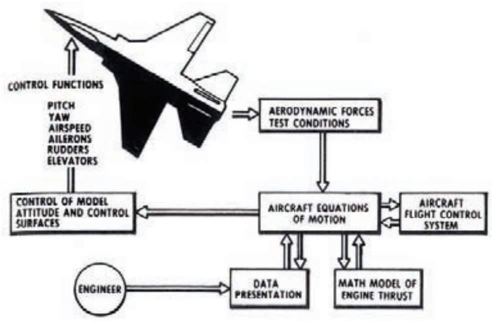
6 DoF nonlinear differential equations of motion

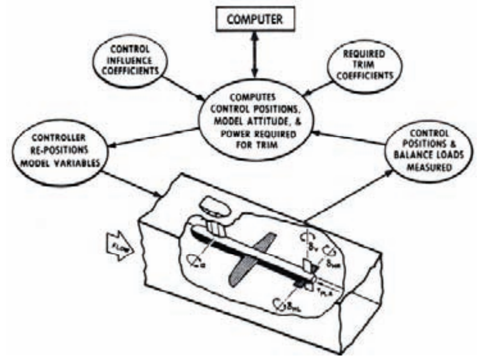
EFD + Flight Dynamics → "Flight Test in WT"

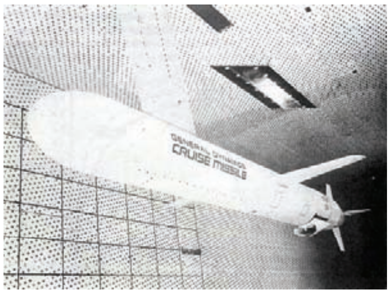
Asai, Nagai, Konno (2010)

Simulation of Flight Maneuvers (AEDC)

The computer is an integral part of the wind tunnel test and several subsystems are combined into a computer-controlled closed loop that allows banks, turns, and stalls to be simulated in an almost hands-off operation.







Asai, Nagai, Konno (2010)

Model Positioning Mechanism (MPM)

Figure 12: Fighter model suspended upside down from the MPM

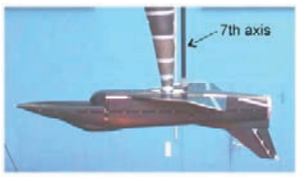


Figure 2. X-31 light-weight model mounted on belly sting with 7th axis.

7th axis (pitching)

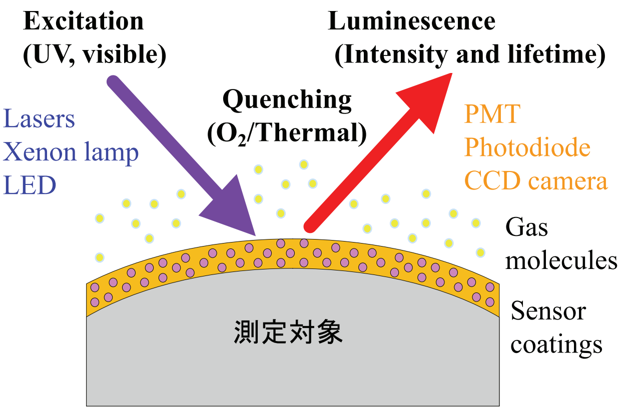
1400N/μm

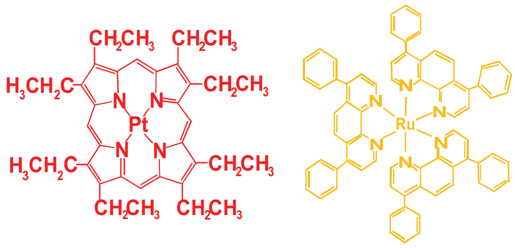
- **6 DoF parallel kinematics (high stiffness)**
- **Use of 6 linear electromagnetic motors (high accuracy/high dynamics)**
- **Max driving frequency <u>3Hz/5deg</u>**

DNW_Annual_Report_2004

Bergmann A et al. MPM. USA Patent Application Pub. No. US 2006/0254380 A1, November 2006.

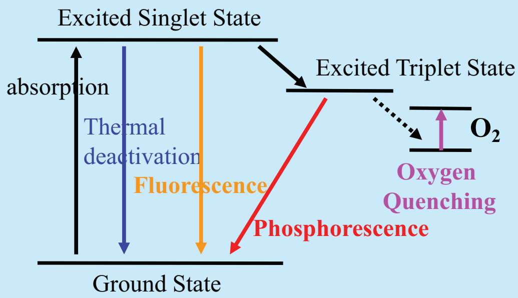
Pressure and Temperature-Sensitive Paints (PSP/TSP)





Sensor Molecules

Principle



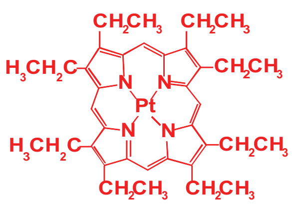
Jablonski Diagram

- **Oxygen Quenching**
  → O_2 concentration (partial pressure) → **PSP**
- **Thermal Quenching**
  → Temperature → **TSP**

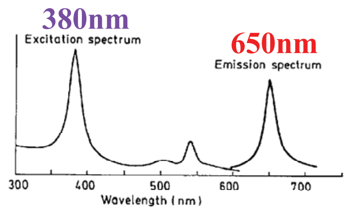
Asai, Nagai, Konno (2010)

Principle of PSP - Oxygen Quenching

- Luminophore: Platinum Octaethylporphyrin (**PtOEP**)
- Binder: Polydimethylsiloxyan (**PDMS**)

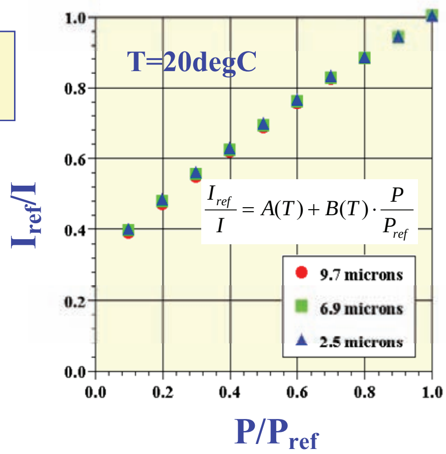


PtOEP

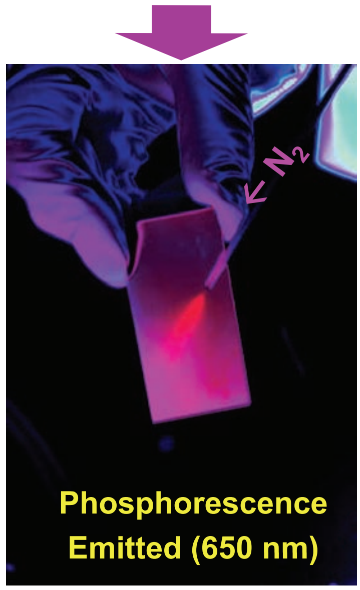


Excitation and Emission Spectrum

Stern-Volmer Relation



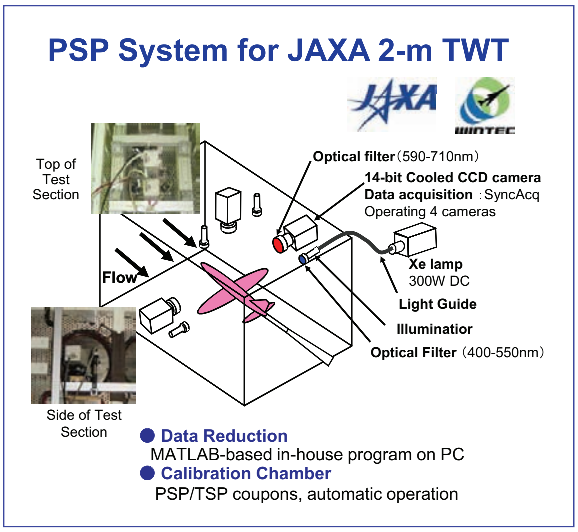
UV illumination

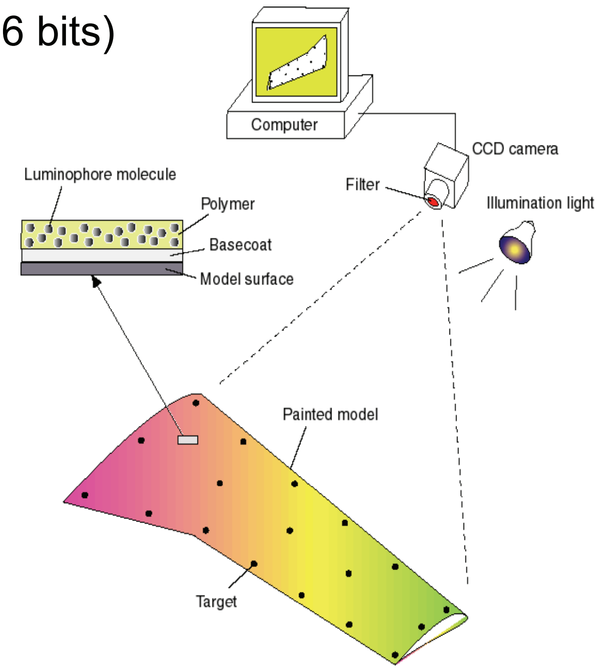


Asai, Nagai, Konno (2010)

PSP/TSP measurement system (imaging)

- Sensor: PSP/TSP coatings
- Excitation light: Xe arc lump, LED
- Detector: CCD camera (12-16 bits)
- Data Reduction: PC-based



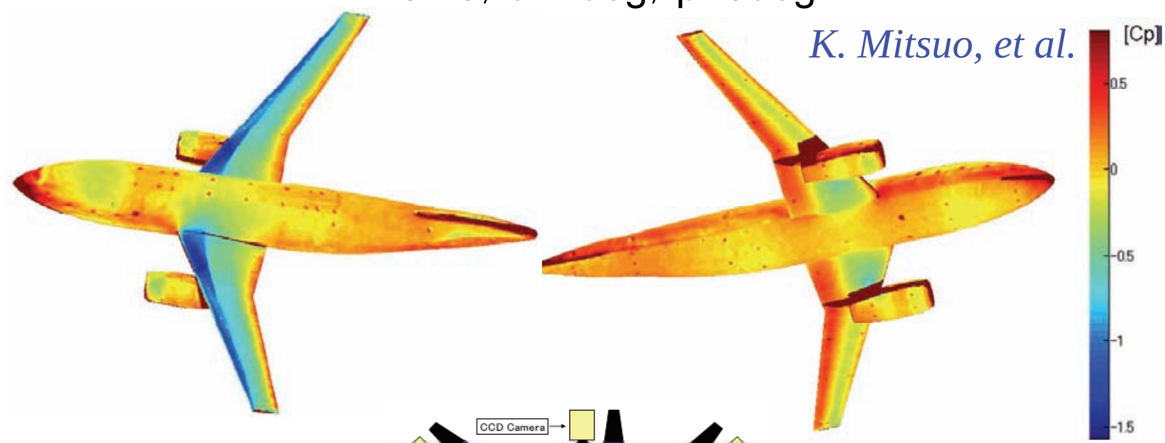


Asai, Nagai, Konno (2010)

PSP Test of DLR F6 model

M=0.75, α=1deg, β=0deg

K. Mitsuo, et al.



DLR F6 model

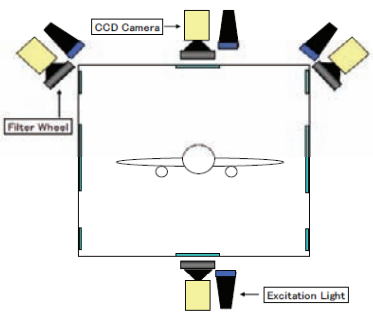
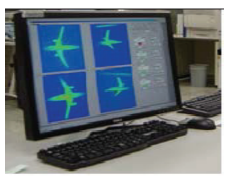


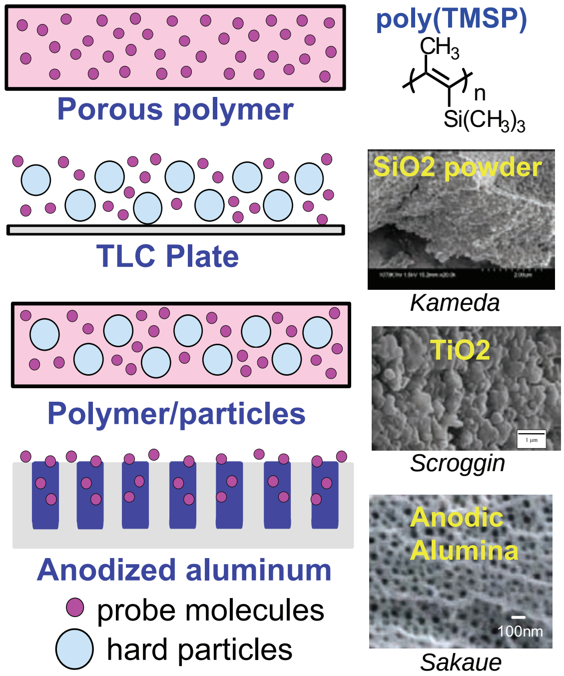
Image Acquisition (4 cameras)



PSP camera images integrated on a model grid.

Fast Responding PSP Formulation

- **Porous Polymer**
  Optrod F1,F2 (1994, 1997)
  Asai et al. (2000)
- **TLC Plate**
  Baron et al. (1993)
- **Polymer/Particles**
  Ponomarev et al. (1998)
  Scroggin et al. (1999)
  Klein (2006)
  Kameda, et al. (2008)
- **Anodized Aluminum**
  Asai et al. (1997)
  Sakaue et al. (1999, 2006)

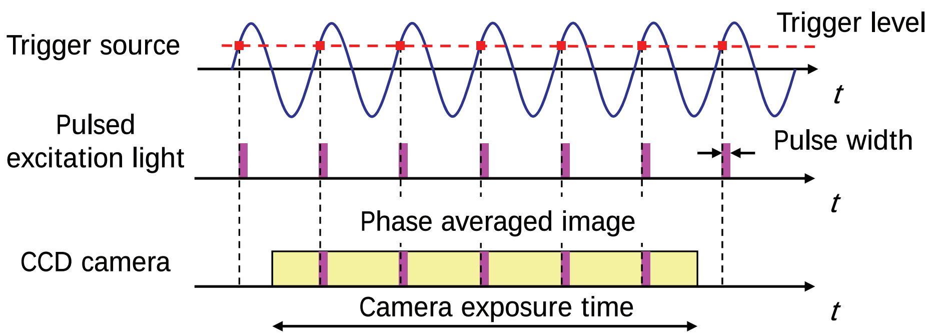


Response time = up to O(10μsec)

Asai, Nagai, Konno (2010)

Phase-lock method

- Applicable to periodic phenomena
- Summing up a small PSP luminescent intensity at the same phase
- Need for a real-time phase detection (trigger signal)

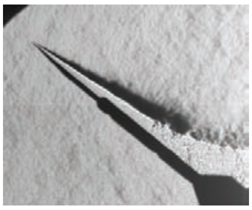


Examples:

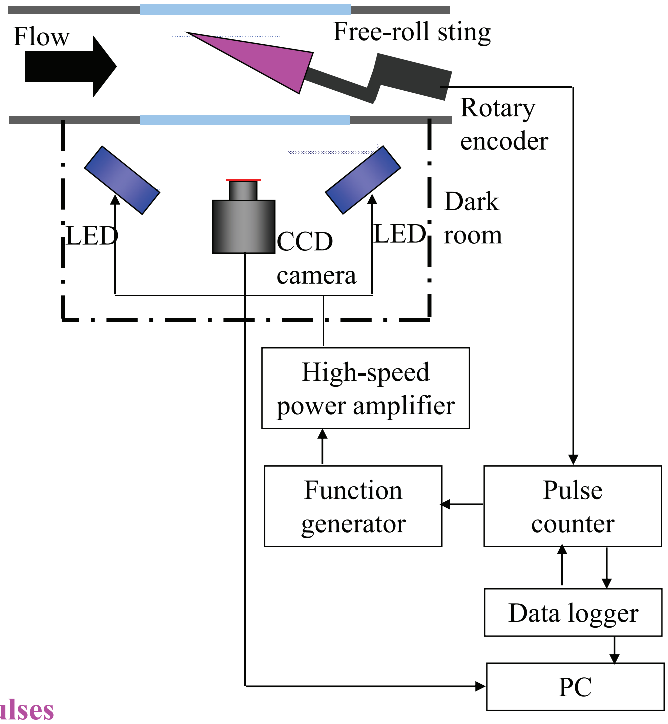
oscillating fence, rotating wings (wing in rocking motion) , acoustic resonance (Hartman tube), ...

Asai, Nagai, Konno (2010)

Unsteady Pressure Measurement on a Delta Wing in Rocking Motion *(Hirose, et al. AIAA 2007-124)*



M=0.5
α=35 [deg]
ϕ_{max}=24[deg]
f =84[Hz]

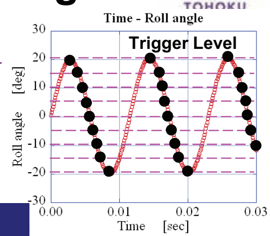


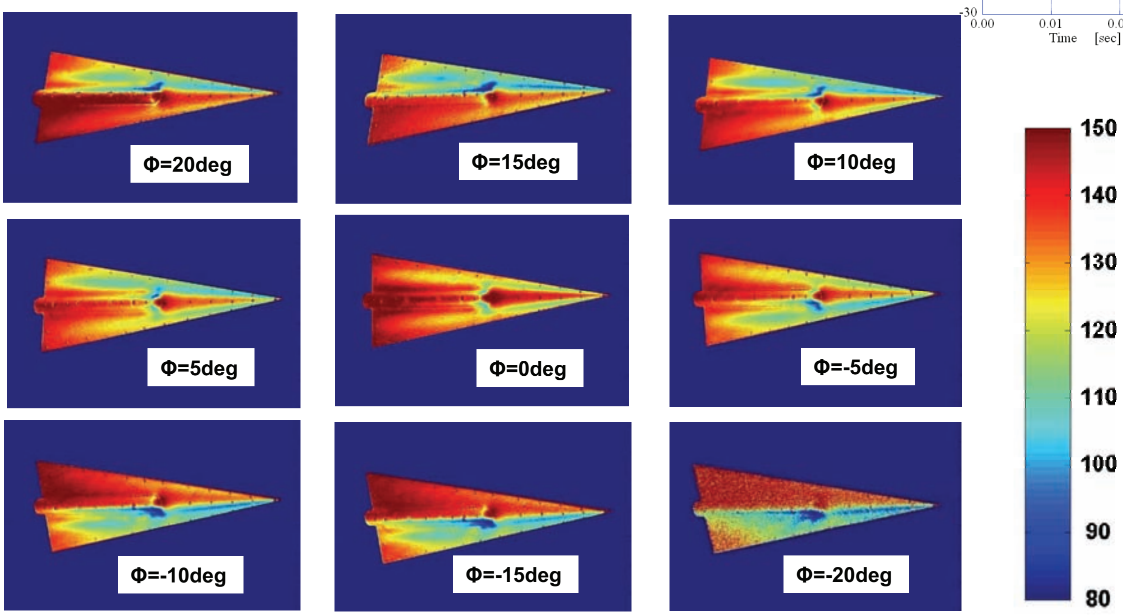
Optical setup

- **Excitation light**
  - UV-LED (λ=395 *nm*)
- **Pulse control**
  - Function Generator
  - High-Speed Power Amplifier
- **Detector**
  - Cooled CCD Camera
    - ･A/D:16bits
    - ･CCD size:1024 × 1024pixels
  - Optical Filter: λ >560 *nm*
  - **Accumulation time : 6000 pulses**

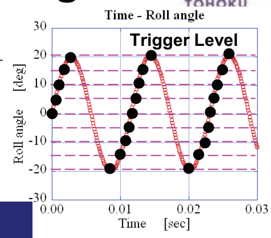
Unsteady Pressure Measurement on a Delta Wing in Rocking Motion *(Hirose, et al. AIAA 2007-124)*

M=0.5, α=35 [deg]
Free-roll, roll rate = positive

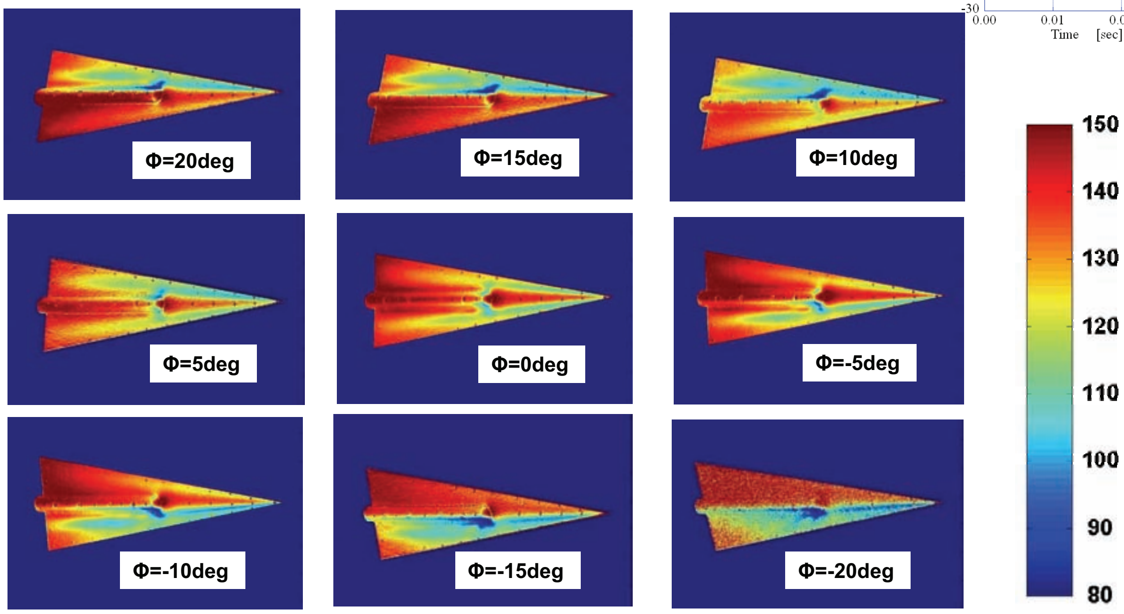




Unsteady Pressure Measurement on a Delta Wing in Rocking Motion *(Hirose, et al. AIAA 2007-124)*

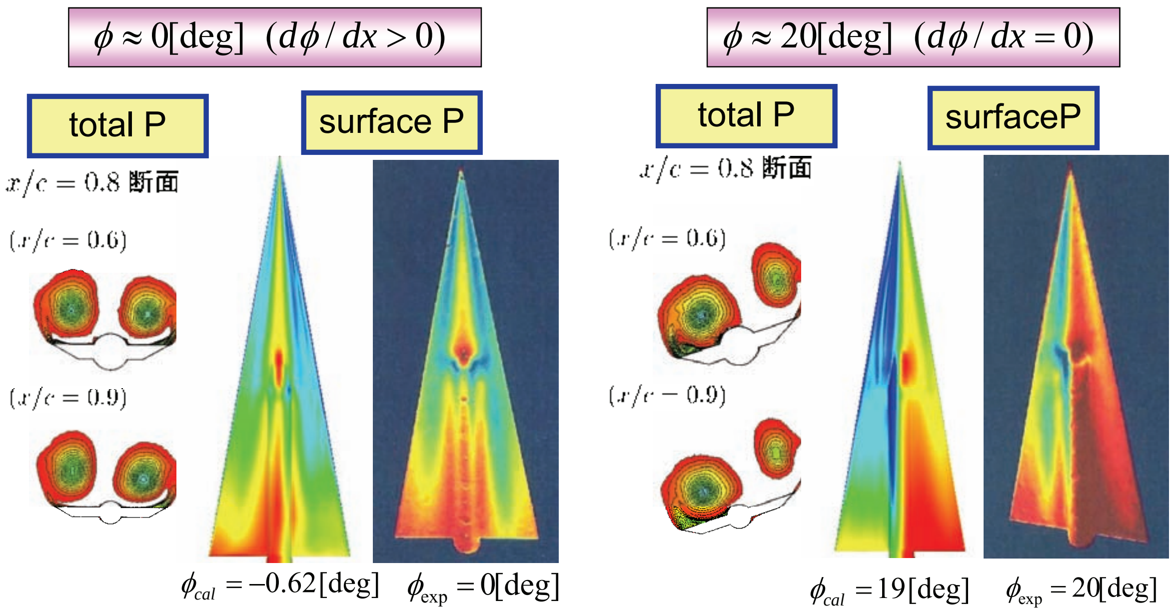


M=0.5, α=35 [deg]
Free-roll, roll rate = negative



Comparison of pressure distribution ～Roll Free～

EFD[CDF] condtions：M=0.5, α=35[deg], Roll Free



(a) CFD　(b) CDF　(c) PSP　(a) CFD　(b) CDF　(c) PSP

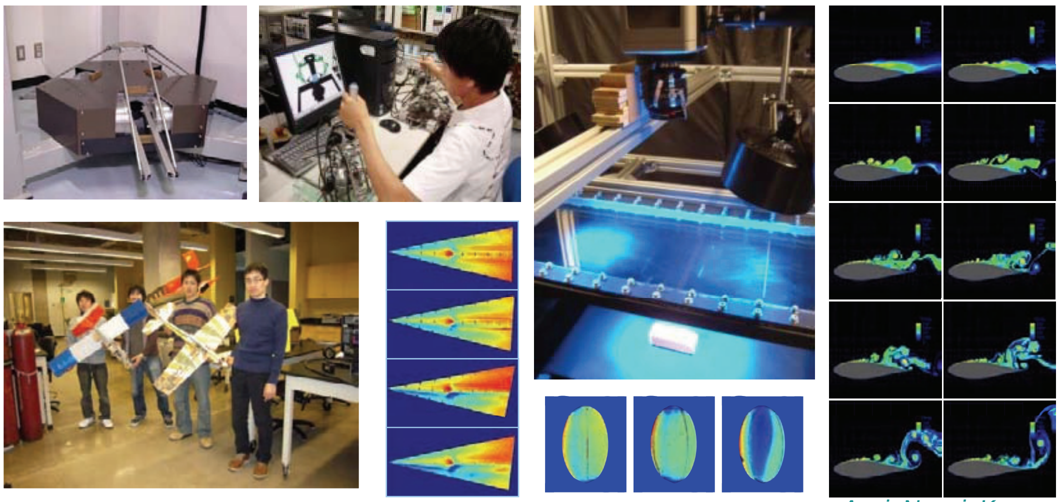
Research Proposal for the Development of *Next-Generation DWT* (Tohoku Univ.)

starting in 2010 (we hope!)

(seeds)

- **Robot Manipulator**
- **Image-based Measurement Techniques**
- **Digital Flight Dynamics**

"Hybrid Flight Simulator"



（山形大共同）

Asai, Nagai, Konno (2010)

Hybrid Motion Simulator HEXA 97

(Uchiyama/Konno Lab., Tohoku Univ.)

Fully parallel robot with rigid links that confer its high rigidity positional accuracy by virtue of the parallel link configurations, reducing the end effector errors

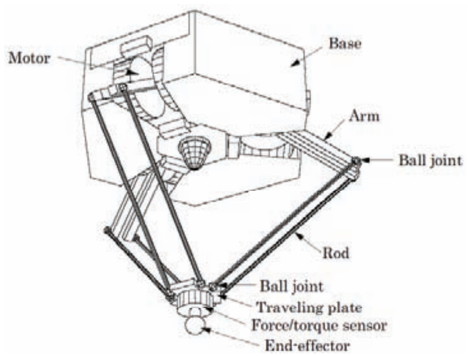


Table A.1: Part sizes of HEXA robot

Items	Sizes mm	Symbols
Offset of the rotational axis of motors	170	H
Length of arm	260	L
Length of rod	480	M
Distance between ball joints	80	$2a$
Offset of the central axis of ball joints	40	h

Table A.1: Major specification the HEXA robot.

Parameter	Size [mm]	Symbols
Offset of the rotational axis of motors	170	H
Length of arm	260	L
Length of rod	480	M
Distance between ball joints	80	$2a$
Offset of the central axis of ball joints	40	h

Table A.2: Standard specification of the HEXA robot.

Parameter	Value-units
Maximum velocity	5.94 [m/s]
Maximum acceleration	22 G
Relative accuracy	0.01 [mm] (Calculated value)
Adept motion cycle time	0.465 [s/cycle]
Weight capacity	10 [kg]
Total weight	60 [kg]

Hybrid Motion Simulator HEXA 97
(Uchiyama/Konno Lab., Tohoku Univ.)

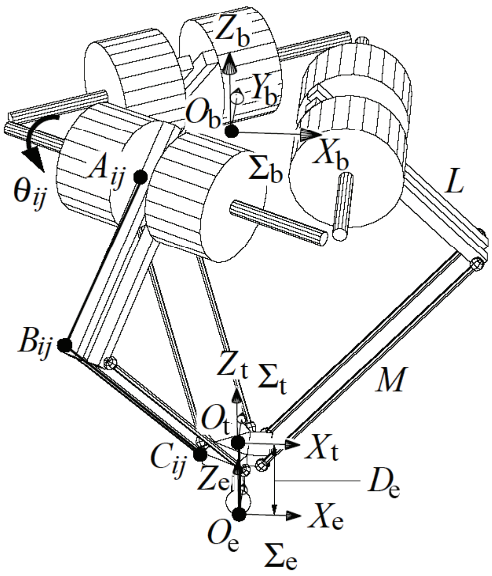


Fig. A.8: Coordinate systems of HEXA robot

Fig. 2.2: Overview of a parallel robot HEXA

Hybrid Motion Simulator HEXA 97
(Uchiyama/Konno Lab., Tohoku Univ.)

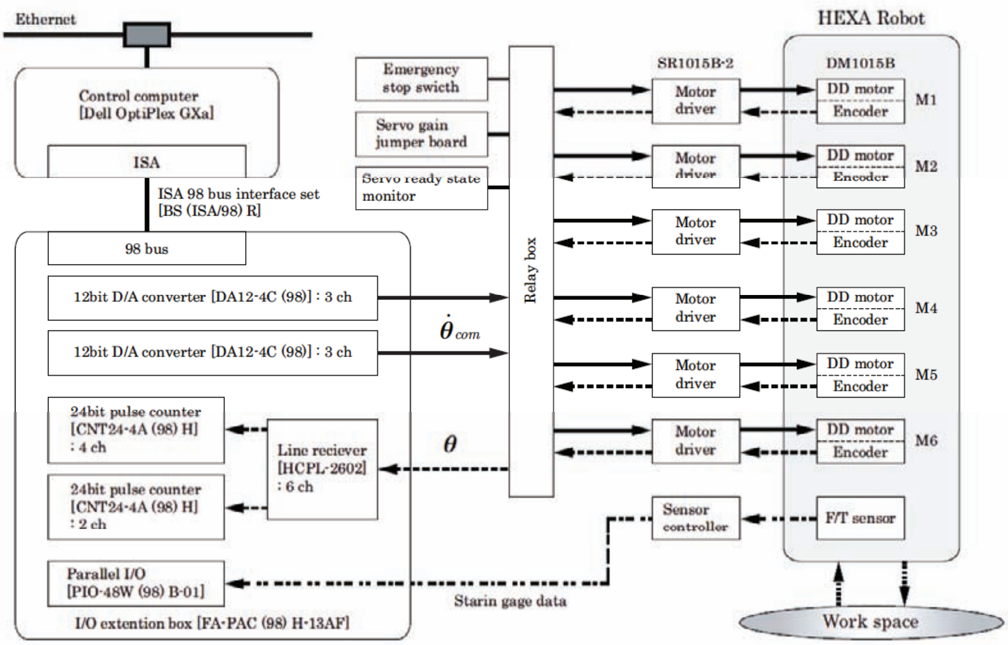


Figure A.7: Configuration of the robot control system [46].

Hybrid Motion Simulator HEXA 97

(Uchiyama/Konno Lab., Tohoku Univ.)

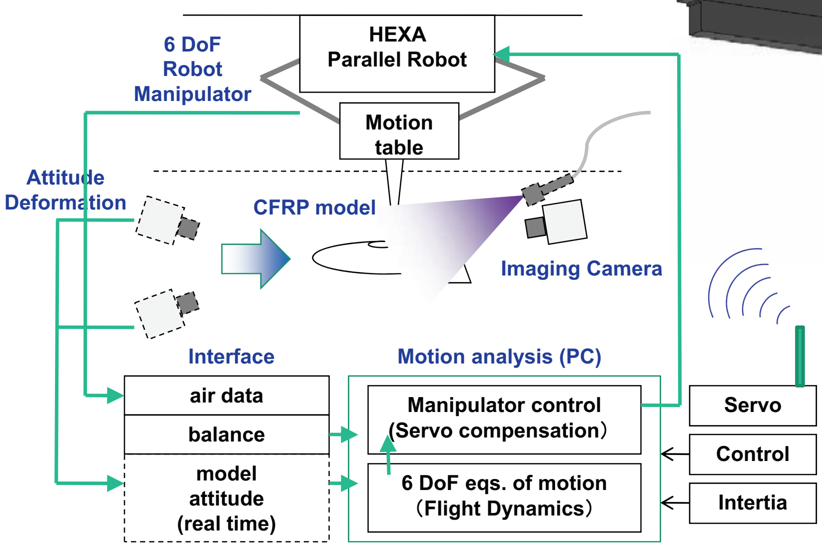
Research Proposal for the Development of *Next-Generation DWT* (Tohoku Univ.)

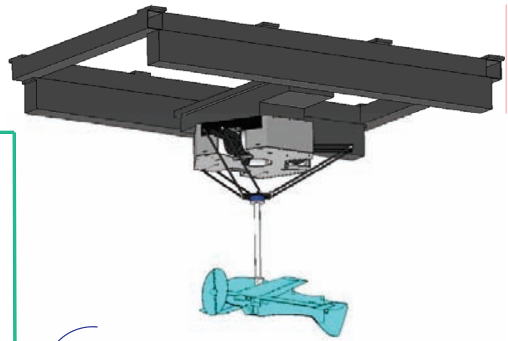
TOHOKU UNIVERSITY

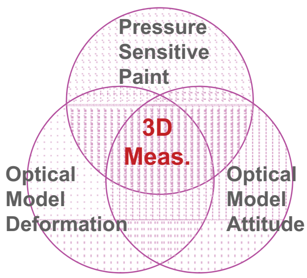
starting in 2010 (we hope!)

"Hybrid Flight Simulator"

Schematic



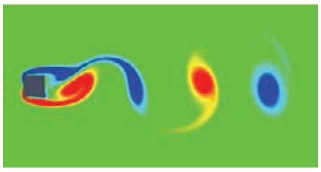




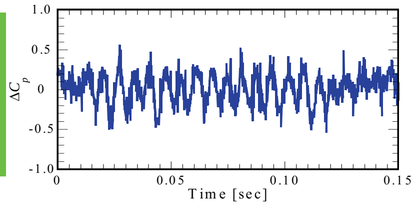
Asai, Nagai, Konno (2010)

PSP application to flow around square cylinder

- periodic phenomena but containing natural disturbance
  → difficult to producing good trigger signal



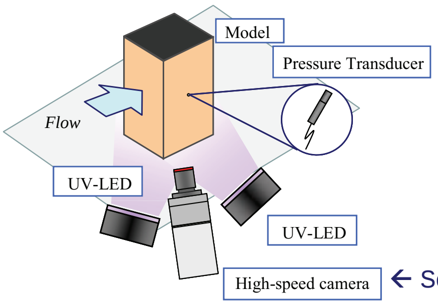
artax.karlin.mff.cuni.cz



Time-series pressure transducer data (p4)

Random noise
Bias drift
Fluctuation of amplitude
Fluctuation of period

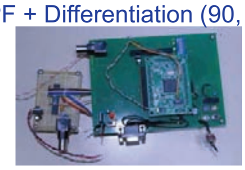
- Our approach: use high-speed C-MOS camera
  1) use conditioned signal for integrating in-phase images (Yorita 2010)
  2) conduct pixel-by-pixel FFT analysis (Nakakita 2007)



← Schematic of measurement setup

Photron, FASTCAM SA5

Bandpass filter (0, 180 deg)
BPF + Differentiation (90, 270 deg)

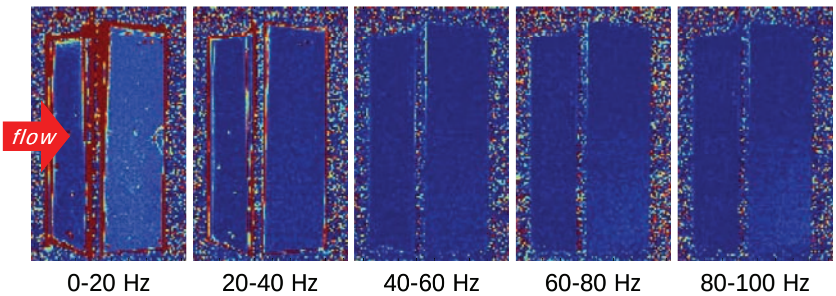


↑ Microcomputer

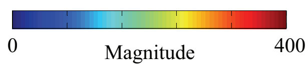
Asai, Nagai, Konno (2010)

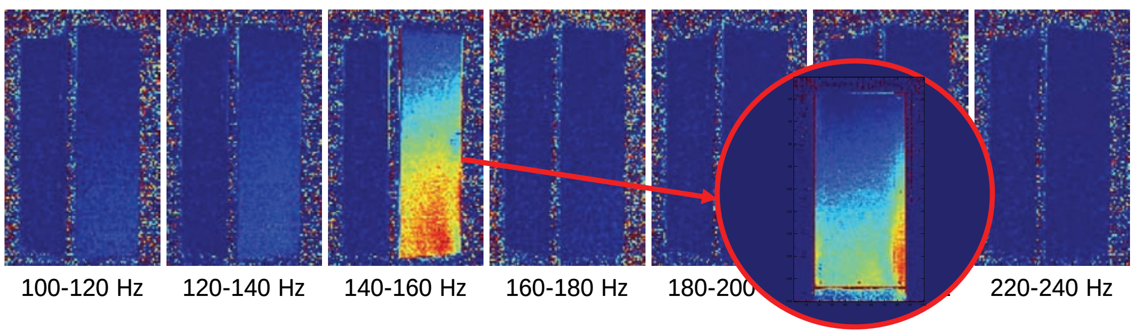
PSP application to flow around square cylinder

- FFT analysis for unsteady PSP measurement (Nakakita's method)



Run	1
Flow velocity	50 m/s
Model angle	0 deg.
Frame rate	500 fps
Camera count	600-1000
Image binning	5*5





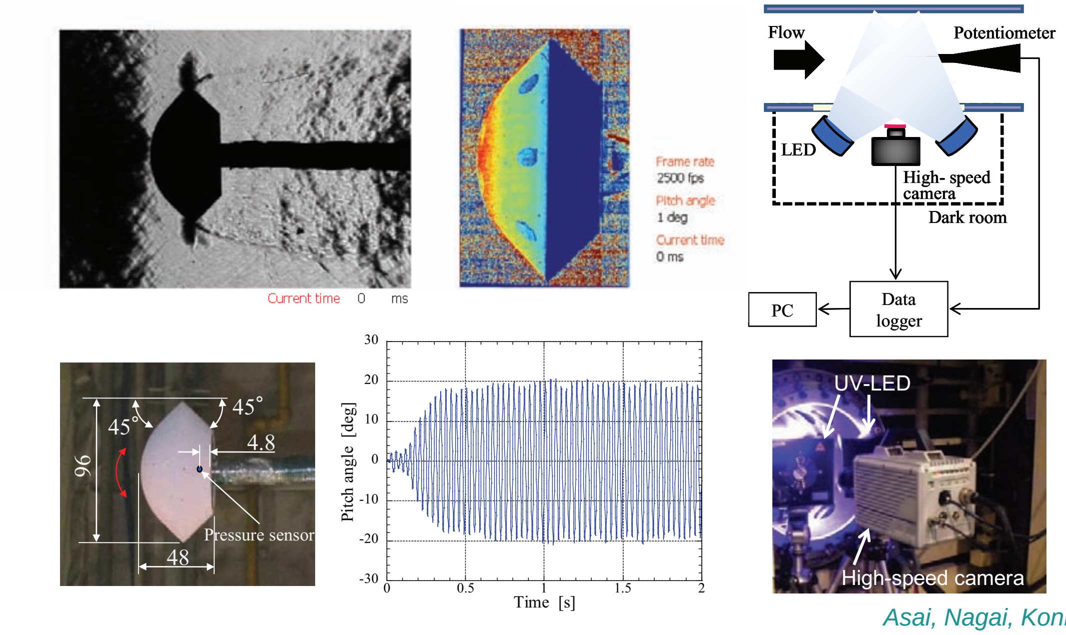
To be presented by D. Yorita at 14th ISFV (June 2010)

Asai, Nagai, Konno (2010)

Application Pressure Sensitive Paint to Dynamic Instability of Re-entry Capsule-shaped Body

D. Sugimoto, et al "Experimental Study on Dynamic Instability of Re-entry Capsule-shaped Body using Pressure Sensitive Paint" AIAA Aerospace Science Meeting (2010)

M=1.1, free-pitch, f=29.9 [Hz]



Asai, Nagai, Konno (2010)

Summary

- Integration of EFD and FD
  EFD+Flight Dynamics → Hybrid Simulator
- Use of State-of-Art Technologies
  Robot Technology (1DoF→6(+α)DoF)
  Image-based 3D measurement
- New role of DWT
  Provide system model (not test data)
  Tool for "Virtual Flight Testing"

Asai, Nagai, Konno (2010)

Questions?

asai@aero.mech.tohoku.ac.jp

Acknowledgements:

D. Yorita, D. Sugimoto, A.Toyoda (students)
K. Kita, Y. Hirose (ex-students)
Prof. K. Nakahashi, Prof. S. Obayashi, Prof. D. Numata (Tohoku Univ.)

Prof. K. Seo (Yamagata Univ.)
Prof. K. Miyaji (Yokohama Nat'l University)
Prof. M. Kameda (Tokyo Univ. Agriculture and Technology)

K. Nakakita, Dr. K, Mitsuo, Dr. M. Yanagihara (JAXA)

Prof. T. Liu (Western Michigan Univ., USA)
Prof. J. W. Gregory (Ohio State Univ., USA)
Dr. C. Klein (DLR,Göttingen, Germany)
Dr. T. Löser (DNW/DLR, Braunschweig, Germany), et al.

Asai, Nagai, Konno (2010)