2012-13 Boeing Higher Education Student Project Presentation

Development of Hybrid Flight Simulator with Multi Degree-of-Freedom Robot

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Background (1)

■ Unsteady Aerodynamics

- The field of use of aircrafts are dramatically expanding
- Unmanned aerial vehicles (UAVs) have a capability of acrobatic flights (Hovering, Turn-around flight, Post-stall maneuver)
- The conventional linear theory based on stability derivatives can not be applied

⇨ **Unsteady aerodynamics**

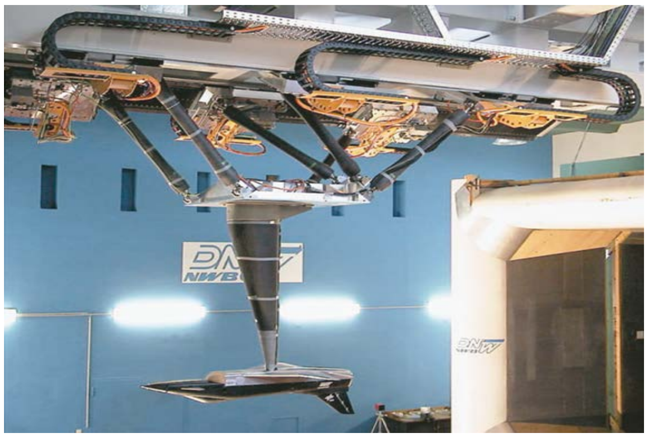
UAV
(Uchiyama Lab, Tohoku univ.)

Post-stall maneuver

Background (2)

■Experimental Fluid Dynamics (EFD)

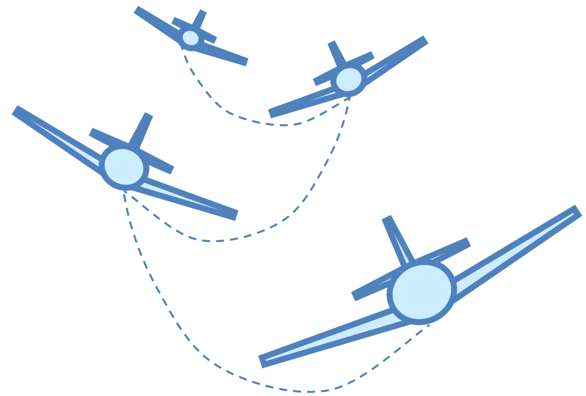
- Dynamic Wind-tunnel testing (DWT)
- Free Flight



MPM(DNW)

■Flight Dynamics

- Calculate behavior of the aircraft



Dutch Roll Motion

EFD + Flight Dynamics = Hybrid Motion Simulation

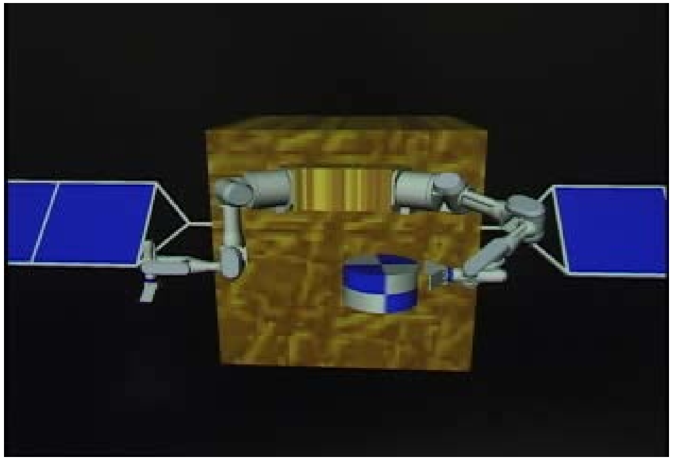
■Hybrid Motion Simulation

- Merge experimental fluid dynamics and numerical simulation
- Arbitrary flights can be demonstrated in the wind tunnel

Past Researches(1)

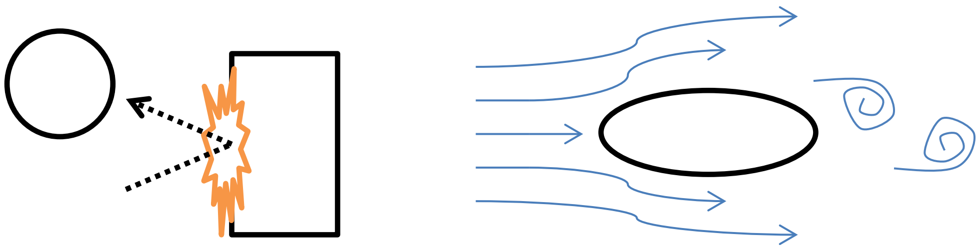
■ Contact phenomena of a satellite

- Only contact phenomena are taken out as a physical model
- Since movement of a model is determined by numerical computation, mass, moment of inertia, etc. can be set up arbitrarily
- This approach can replace other physical models



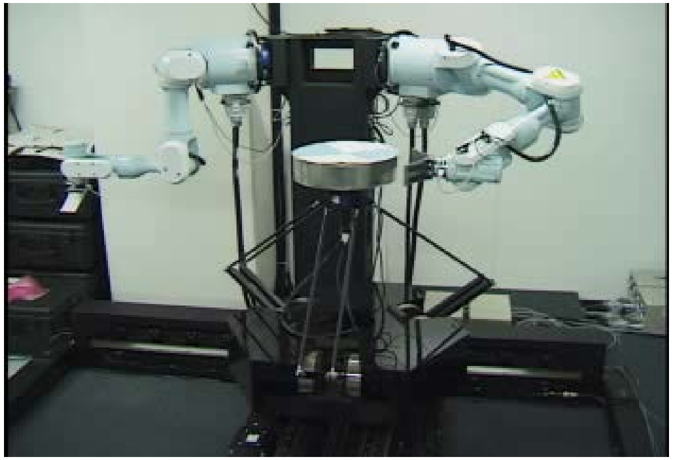
Numerical model

■ Hybrid Flight Simulation



Contact phenomena ⟶ Aerodynamic phenomena

⇨ **New application**

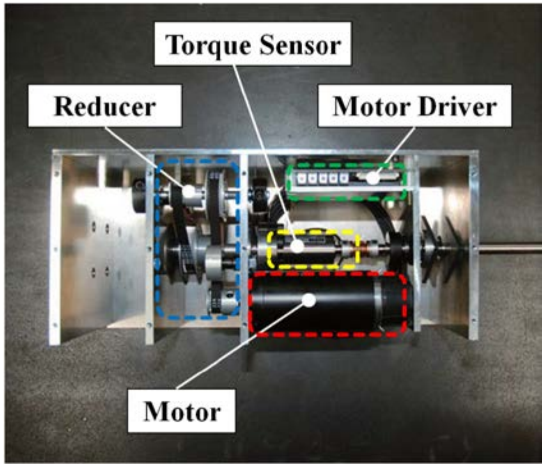


Physical model

Past Researches(2)

■ Wing Rock Phenomenon

- Wing Rock is a dynamic behavior of delta wing model at high angle of attack
- Self-induced limit cycle oscillation
- Rotational movement of yaw and roll axes

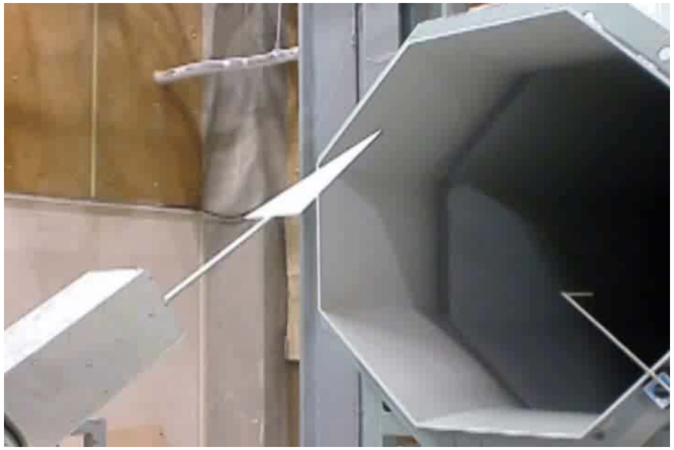


Rolling motion device

■ 1-DOF Hybrid Flight Simulation

- Using simple delta wing model
- Motion is restricted within roll axis
- AoA=35 [deg], u=10 [m/s]
- Limit cycle can be confirmed

⇨ **Increasing Degree of Freedom**



Hybrid Motion Simulation

Objectives

Development of Hybrid Flight Simulator with Multi-Degree-of–Freedom Robot

Reproduce simulated flight tests in Wind-tunnel using a multi degree-of-freedom robot

- Forced Oscillation Wind-Tunnel Testing
  - To investigate the stability properties of the model
- Flight Testing
  - To obtain the real flight data
- Initial Hybrid Flight Simulation in Wind-Tunnel
  - To verify the problems developed for the Hybrid Flight Simulator

Multi-DOF Hybrid Motion Simulation

■ **System Concept**

- Using 6-DOF robot manipulator
- Evaluates as compared with R/C model

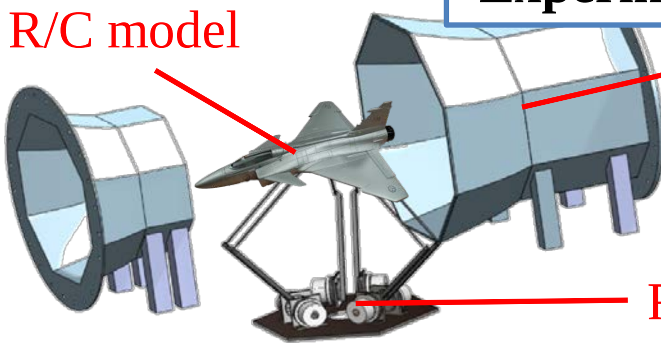
Get flight data from R/C model

Hybrid Motion Simulation

Experimental model

R/C model

Wind-tunnel



Robot manipulator

Demonstrate the unsteady motion using by robot

Numerical model

Calculate the flight dynamics the obtain data

Force and Torque sensor

Measuring aerodynamic force and torque

Development of 6-DOF Robot Manipulator

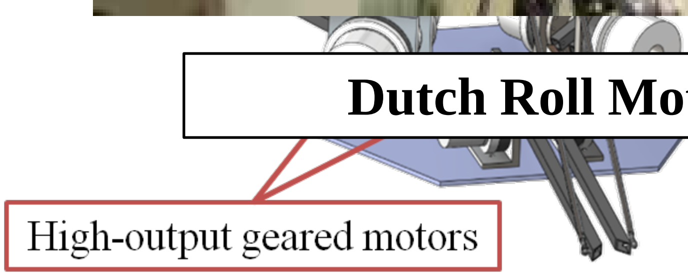
■HEXA-X2

- Uchiyama Lab
- HEXA-X2 is a

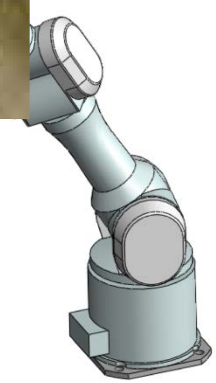
■The merit of

- Supported by r
- Light weight ar

Dutch Roll Motion (3Hz)



HEXA-X2 (Parallel Robot)



PA-10 (Serial Robot)

R/C Aircraft Model

■Requirement

(1) Delta-wing aircraft

(2) High mobility capable for high AoA flight

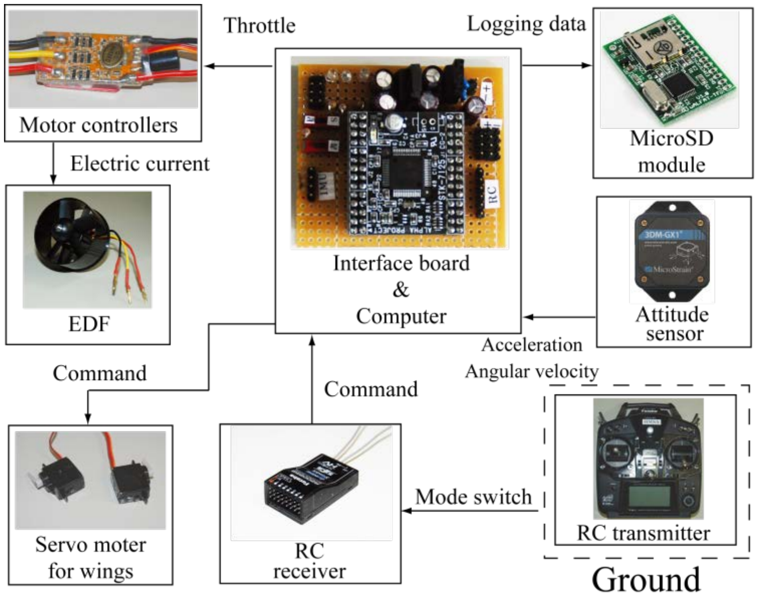
(3) Blockage rate is under 20%

Model	Mini JAS-39 Gripen EDF Fighter Jet
Length [mm]	700
Wing chord [mm]	300
Wing span [mm]	510
Sweep angle [deg]	55
Weight [g]	360

Mini JAS-39 Gripen EDF Fighter Jet

■Electronics system

・IMU measure the model's attitude, acceleration and velocity



On-board electronics system

Numerical Calculation

■Equation of motion

- Translation

$$m\dot{V} + m(\omega \times V) = F$$

- Rotation

$$I\dot{\omega} + \omega \times I\omega = G$$

M : Mass
I : Inertia tensor
F : Force
G : Torque
V : Velocity
ω : Angular velocity

Force & Torque → **Equation of motion** → **Acceleration & Angular acceleration**

■ Calculate model's position and attitude

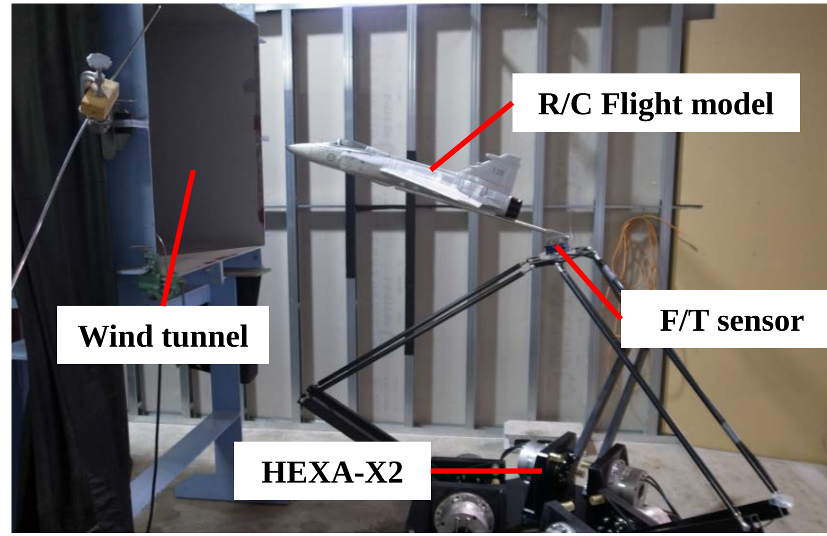
- The position and attitude of the model are calculated by integrating acceleration and angular acceleration.

Acceleration & Angular acceleration → **Velocity & Angular velocity** → **Position & Attitude**

Forced Oscillation Wind-Tunnel Test

■Experimental Setup

- Frontier Wind-tunnel
  - Test section size : 790 [mm] × 790 [mm]
  - Blockage rate : 18% (at AoA=40 [deg])
- HEXA-X2
- F/T sensor (Fx, Fy, Fz, Nx, Ny, Nz)

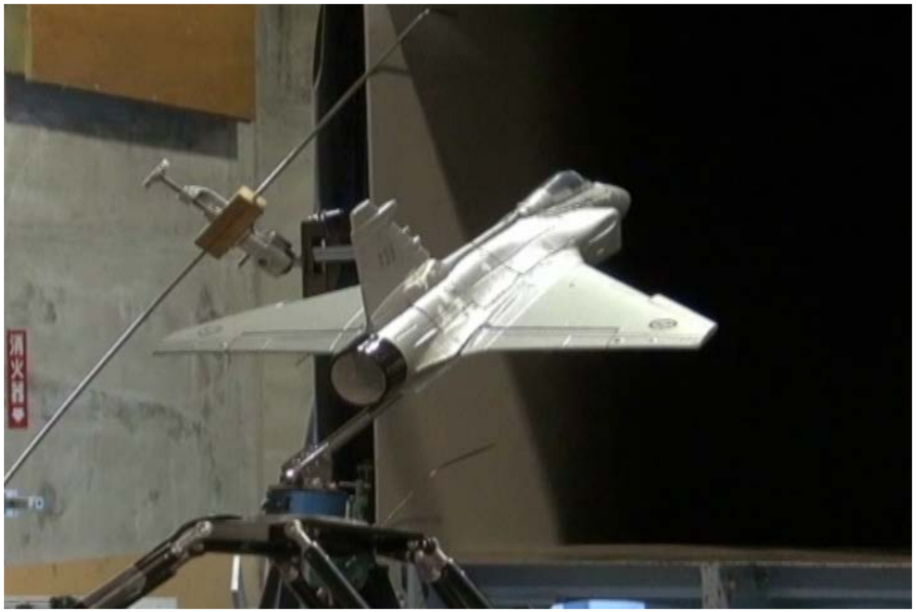


■Test Condition

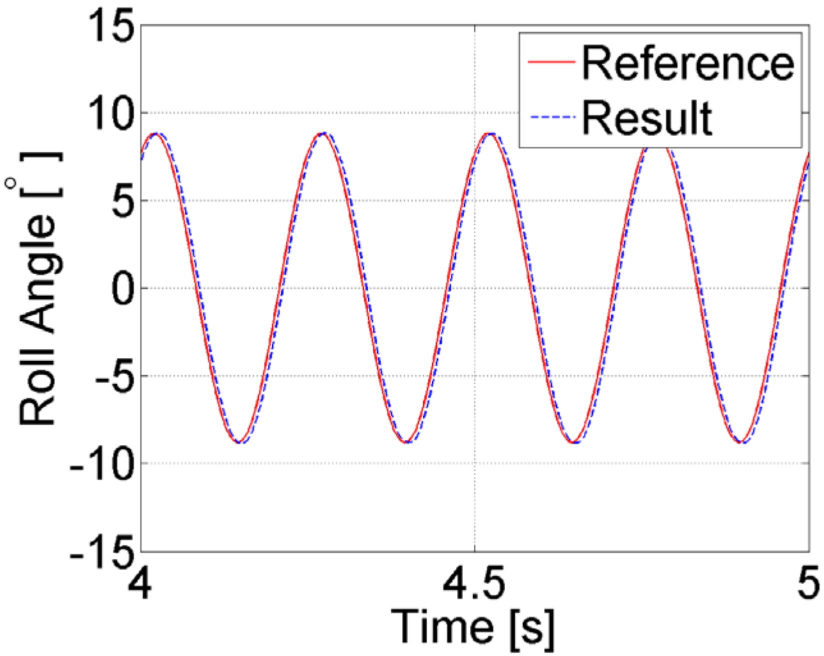
- Evaluation of moving frequency
- Forced oscillation test
  - The effect of angle of attack
  - The effect of frequency

Parameters	
Wind velocity [m/s]	10
AoA [deg]	10, 20, 30, 40
Oscillation Frequency [Hz]	0.5, 1.0, 1.5
EDF Thrust [%]	100

Result (Evaluation of Moving Frequency)



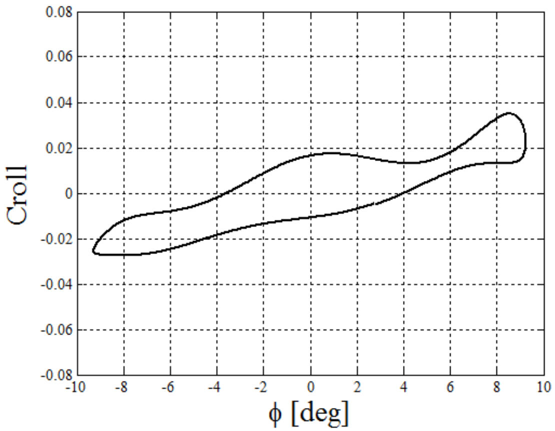
f= 4Hz, Δφ=10deg



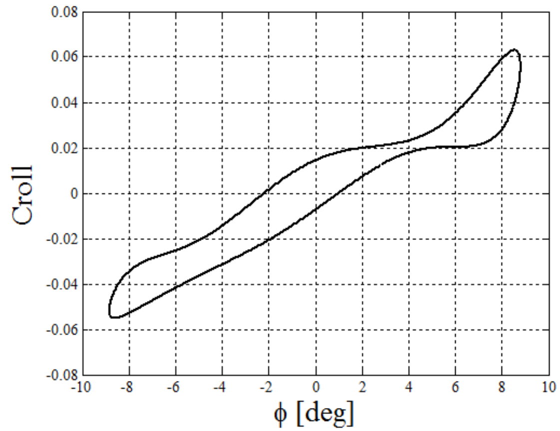
Time-series data of roll angle

- The control of the robot HEXA-X2 functioned well and the commanded roll angle profile was well traced.
- This result verified the capability of the developed robot for tests with high speed (4Hz).

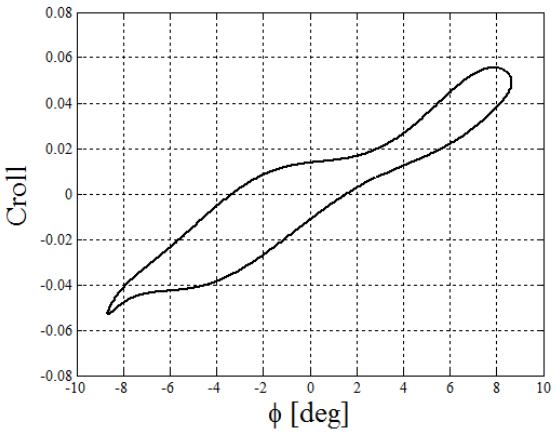
Result (The effect of AoA)



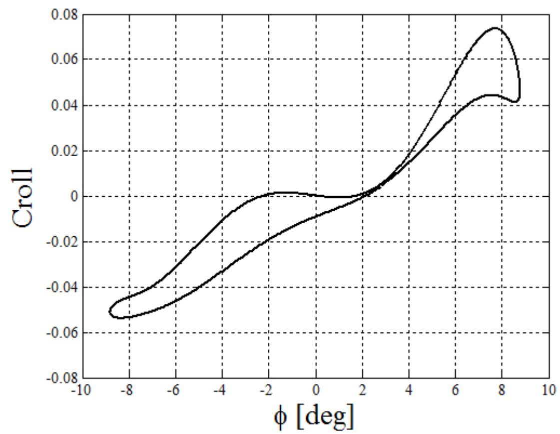
AoA=10°



AoA=20°



AoA=30°

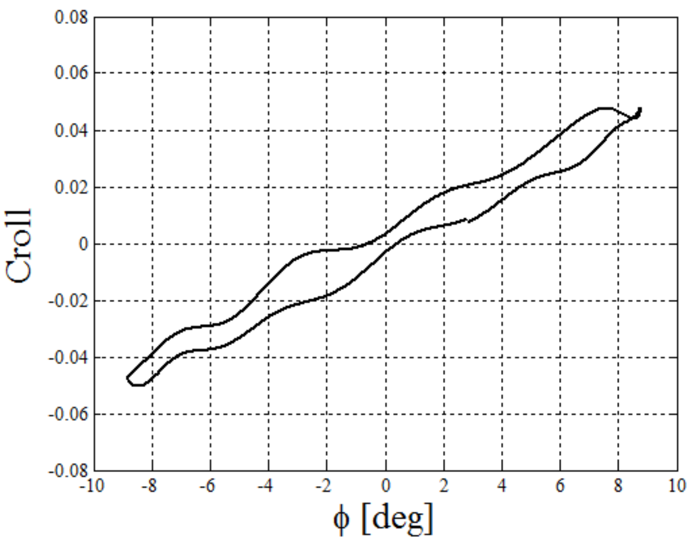


AoA=40°

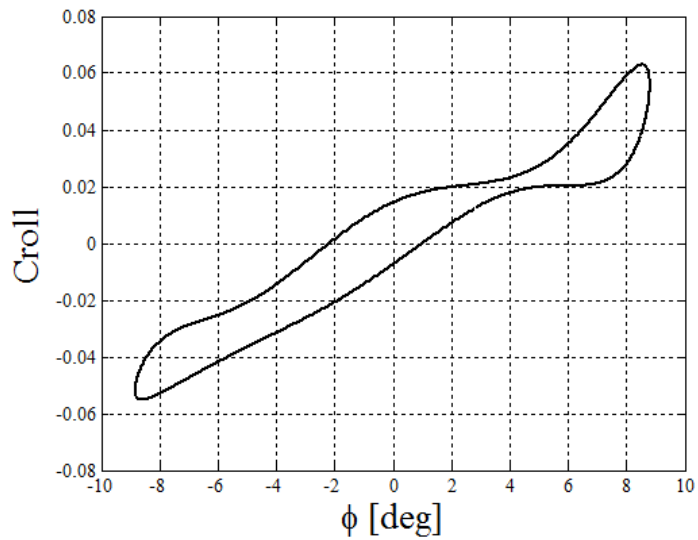
f= 1Hz
Δφ=10deg
u=10m/s
Thrust=100%
LPF=5Hz

・This result indicates that while the angle of attack is increased, the amplitude is increased and the symmetry of hysteresis loop is broken.

Result (The effect of frequency)



f=0.5 Hz



f=1.0 Hz

AoA=20°
Δφ=10deg
u=10m/s
Thrust=100%
LPF=5Hz

- The hysteresis becomes large with increasing frequency, while the area of loop is increased.
- It is considered that this nonlinear behavior of the rolling moment is due to the number and position of breaking down of a leading-edge and tip of the model separation vortex.

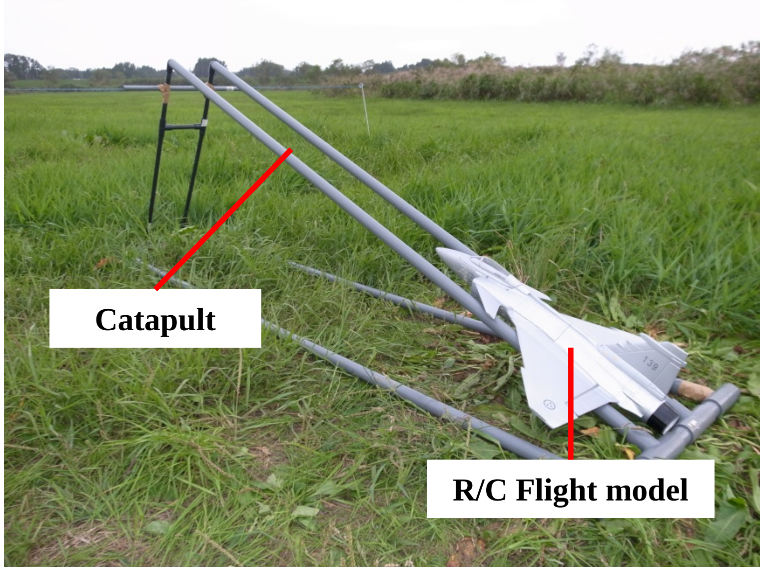
Flight Testing

■Experimental Setup

・Flight test was conducted at a reverbed of Osato town, Miyagi.

・Using a catapult in order to give the initial velocity for R/C model. (about 3 m/s)

・The wind disturbance was low.



■Test Condition

・The R/C model was launched toward the windward.

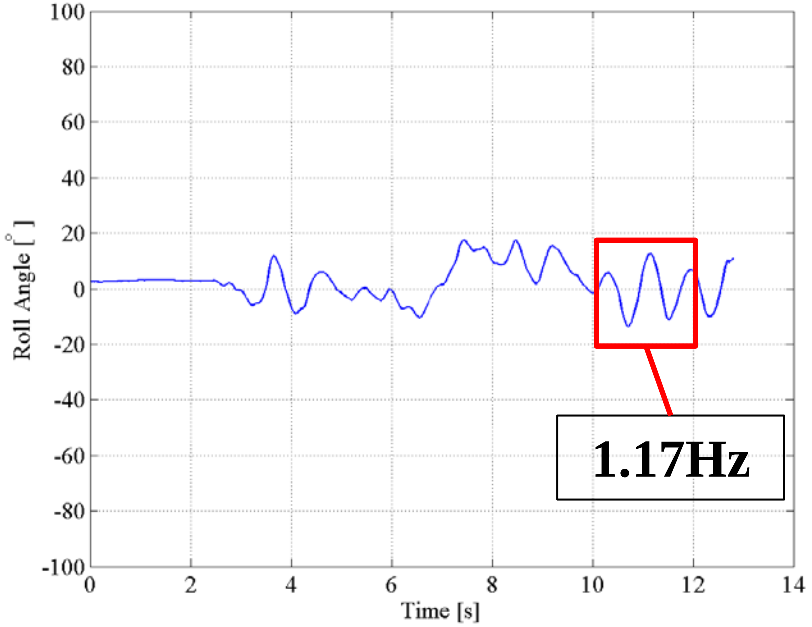
・IMU was initialized when the R/C model is horizontal state.

Parameters	
Atomospheric pressure [hPa]	1019.82
Wind velocity [m/s]	1.93
Temperature [degC]	22.2
Model weight [g]	360
Battery capacity [mAh]	550

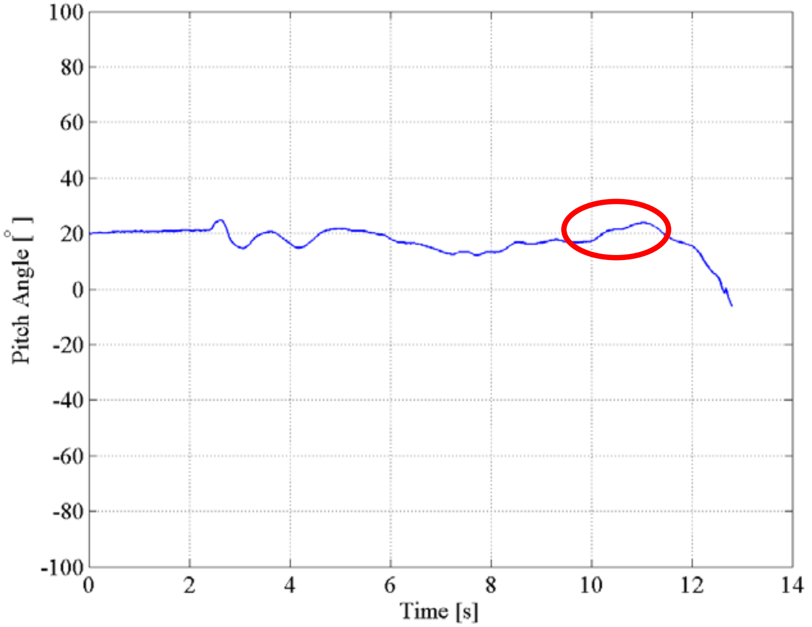
Result of Flight Testing

Result of Flight Testing

Analysis of Unsteady Behavior



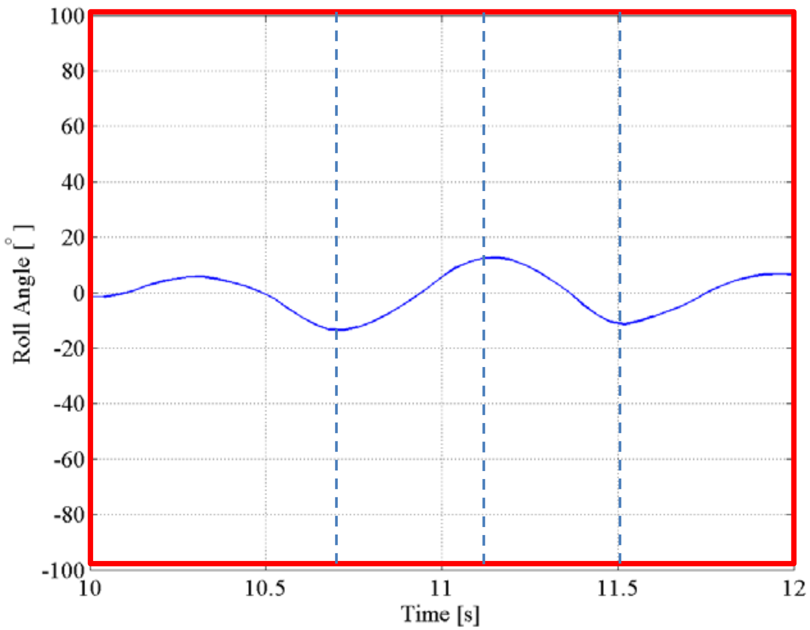
Roll angle



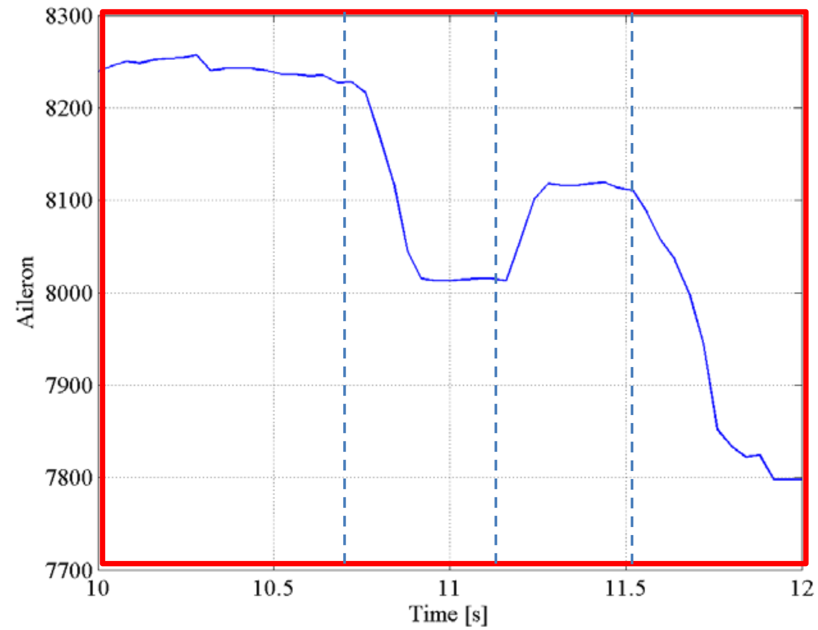
Pitch angle

- It can be seen that unsteady behavior is identified in roll axis at around 12x seconds.
- Pitch angle is increased slightly at the same time, which indicates the instability of the R/C model in roll axis.

Analysis of Unsteady Behavior



Roll angle (10-12 sec)

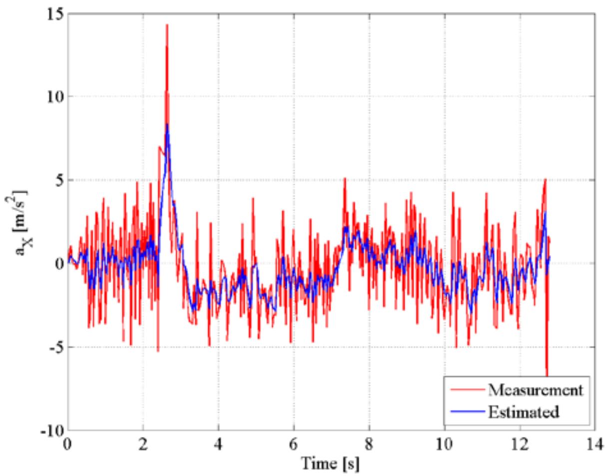


Time history of Aileron (10-12 sec)

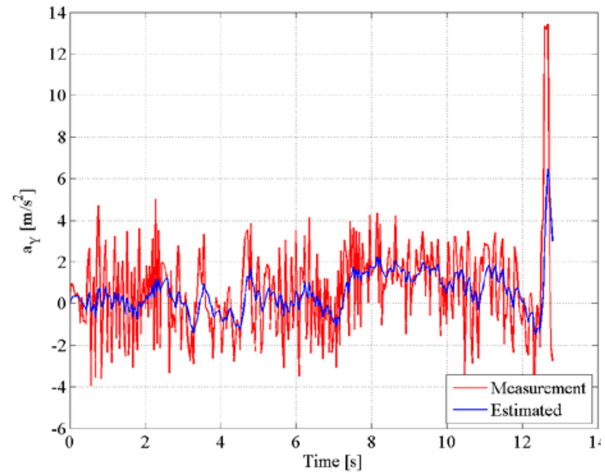
- It can be seen that the control surface (aileron) is input in response to changes in the roll angle.
- It is necessary to introduce the automatic control instead of the control of pilot.

Result (Flight data of Acceleration)

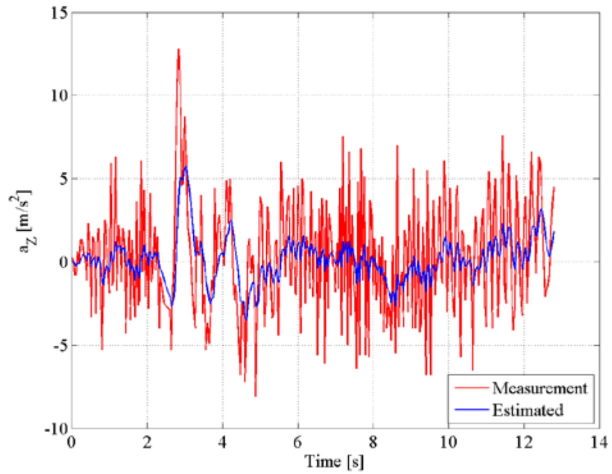
Red line = Raw data
Blue line = Filtered data



X-direction



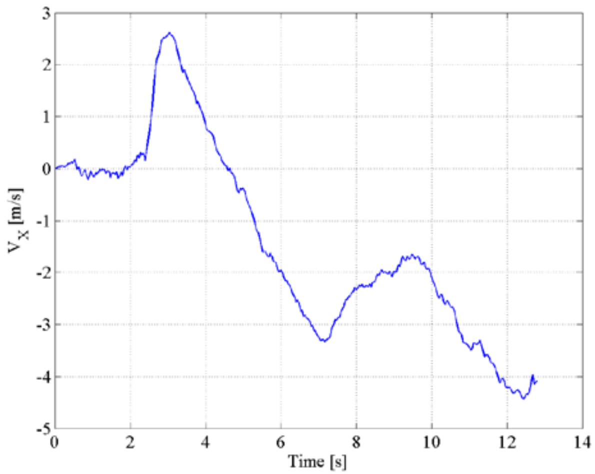
Y-direction



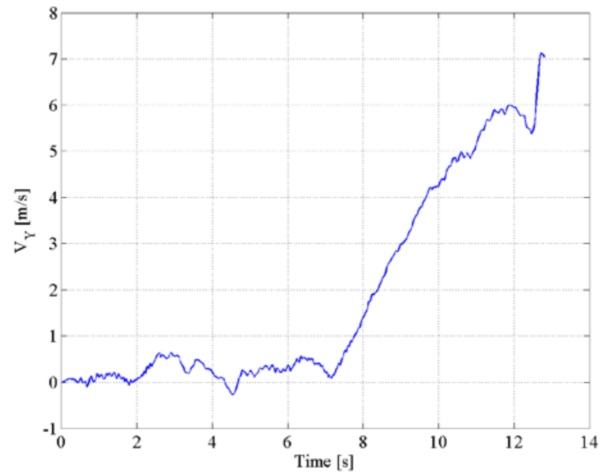
Z-direction

- In order to acquire more probable value, we used Kalman filter because raw data of acceleration is so noisy.
- The flight model launched from the catapult system at around 2 seconds and crashed at around 13 seconds.
- A large acceleration can be considered as the moment of launch and crash.

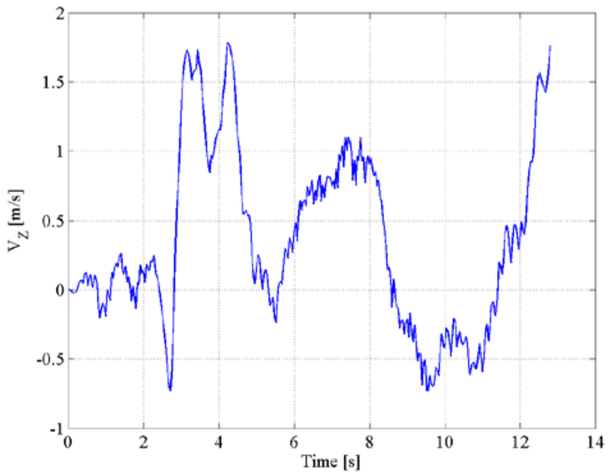
Result (Flight data of Velocity)



X-direction



Y-direction



Z-direction

- It is impossible to calculate the flight speed with sufficient accuracy by simply integrating these data.
- In order to improve the accuracy of the velocity measurement, it is needed to be equipped with some more accurate devices.

Hybrid Motion Simulation Testing

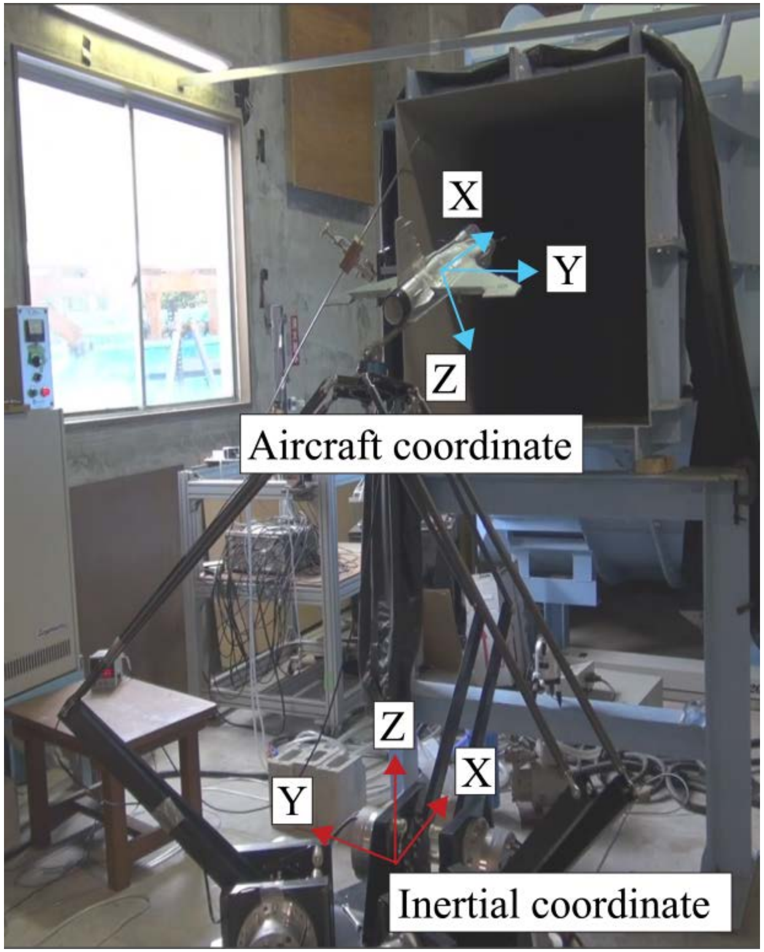
■ Experimental Setup

- Frontier Wind-tunnel
- HEXA-X2
- F/T sensor (Fx, Fy, Fz, Nx, Ny, Nz)

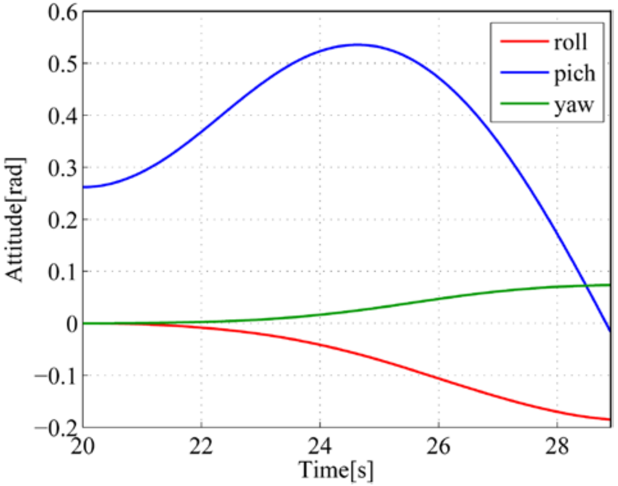
■ Test Condition

- The operator input the elevator to change pitch angle.

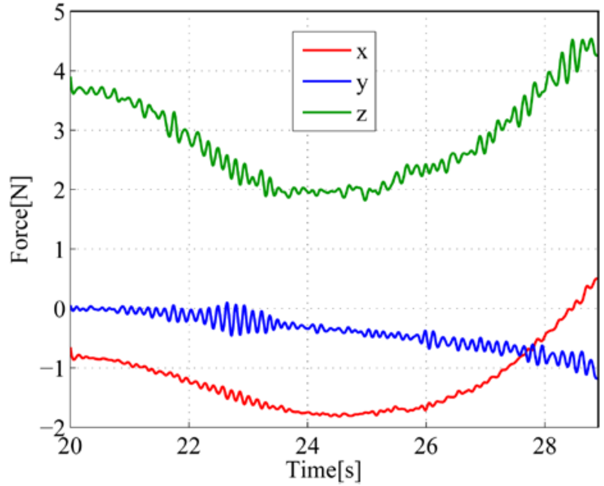
Parameters	
Angle of attack [deg]	15
Wind velocity [m/s]	10



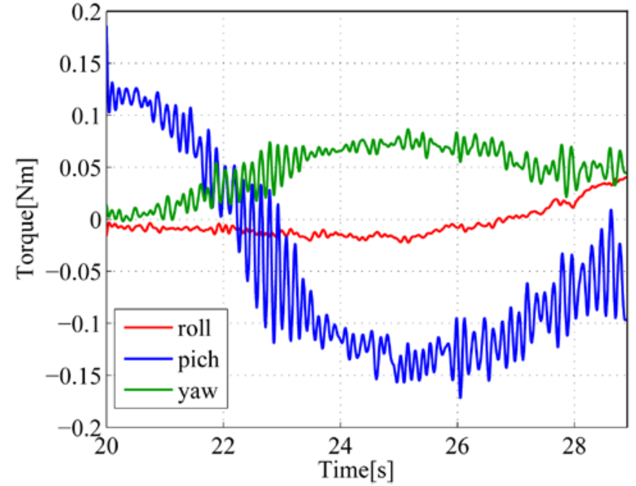
Result of HMS



Attitude



Force



Torque

- In order to process the force/ moment measurement a low pass filter of the cut-off frequency 10 [Hz] is employed.
- The data measured in the experiments indicates that when the operator tried to change the orientation of R/C model, it behaved accordingly as if in the condition of real flight.

Conclusion

- We have developed a hybrid flight simulator for dynamic wind-tunnel testing.
- In order to realize multi degree-of-freedom motion, we developed HEXA-X2, 6 degree-of-freedom robot manipulator, and it can realize 4[Hz] rolling.
- Forced oscillation wind-tunnel testing results indicated that nonlinear behavior of the rolling moment can be identified and the reason for it is considered as the number and position of break down of a leading-edge and tip of the model separation vortex.
- Flight test of R/C model to gather the flight data for validation is necessary for hybrid motion simulation. Roll-direction unsteady behavior of R/C model was observed at the high angle of attack.
- As for the hybrid motion simulation, currently initial tests were completed, in which physical parameters larger than the practical value are used in order to ensure stability.

Future Works

■Forced Oscillation Wind-tunnel Testing

・In order to elucidate this phenomenon, we will conduct flow visualization experiment and determine the structure of leading-edge and tip of the model separation vortex.

■Flight Testing

・In order to improve the accuracy of the velocity measurement, it is needed to be equipped with some devices.

■Hybrid Motion Simulation

・After some further improvements, for example the delay of system, it is expected that the proposed hybrid flight simulator can be used as a powerful tool for aerodynamics research.

Thank you for your attentions!