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

- **Flight Dynamics**
  - Calculate behavior of the aircraft

**Hybrid Motion Simulation**

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

■ 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

■ Hybrid Flight Simulation

Contact phenomena ➔ Aerodynamic phenomena

New application
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

- 1-DOF Hybrid motion simulation
  ex.) Wing rock (limited 1-DOF)
- Multi-DOF Hybrid motion simulation
  ex.) Wing rock, Dutch roll
Hybrid Motion Simulator

■ Outline of Hybrid Motion Simulator
  • EFD (Experimental model)
  • Flight dynamics
    (Numerical model)

Numerical model
  Dynamics calculation
  position and attitude

Experimental model
  Servo mechanism
  Model positioning

Force and Torque (F/T) Sensor
  Measuring force and torque

2013/3/29
1-DOF Hybrid Motion Simulation (1)

■ 1-DOF Wing Rock Motion (Free Roll)

- Wing Rock is a dynamic behavior of delta wing model at high angle of attack
- Self-induced limit cycle oscillation
- AoA=35 [deg], \( u=10 \) [m/s]

\[ f=3.2 \text{ [Hz]} \]

Free Roll Device

Free Roll (Wing Rock)
1-DOF Hybrid Motion Simulation (2)

- 1-DOF Wing Rock Motion (Hybrid Motion Simulation)
  - Compared Hybrid Wing rock motion with free roll motion
  - AoA=35 [deg], $u=10$ [m/s]

$\quad f=1.15$ [Hz]

Rolling motion device

Need to increase the accuracy

Hybrid Motion Simulation
Cause of the problem

- Process hold-up time of Hybrid Motion Simulator

**Calculation delay**

- Dynamics calculation
  - position and attitude

**Sensor delay**

- F/T Sensor
  - Measuring force and torque

**Servo mechanism**

- Model positioning

**Servo delay**

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1-DOF Hybrid Motion Simulation (3)

■ Phase-Lead Compensation

- Phase-lead compensation (PLC) is introduced
- Compensate for the sensor delay
- AoA=35 [deg], $u=10$ [m/s]

$\frac{T s + 1}{\alpha T s + 1}$

$\Rightarrow$ Compensate for other delays

$\Rightarrow$ Hybrid Motion Simulation (PLC)

$f=1.95$ [Hz]
Multi-DOF Hybrid Motion Simulation

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

Hybrid Motion Simulation

**Numerical model**
- Evaluate model position & attitude
- Dynamics simulation

**Experimental model**
- Exercise experimental model
- Measure aerodynamic force

Get flight data from R/C model

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Development of 6-DOF Robot Manipulator

■ HEXA-X2

- Uchiyama Lab. in Tohoku University developed HEXA-X2
- HEXA-X2 is a Parallel link robot manipulator

■ The merit of HEXA-X2

- Supported by multiple arms → High rigidity
- Light weight arms → High frequency

PA-10 (Serial Robot)  HEXA-X2 (Parallel Robot)
Development of 6-DOF Robot Manipulator

■ HEXA-X2
  • Uchiyama Lab. in Tohoku University developed HEXA-X2.
  • HEXA-X2 is a Parallel link robot manipulator.

■ The merit of HEXA-X2
  • Supported by multiple arms.
  • Light weight arms.

HEXA-X2 (Parallel Robot)  PA-10 (Serial Robot)
Dutch Roll Motion (3Hz)  High-output geared motors
6-DOF

Workshop on Next Generation Transport Aircraft

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Summary and Future Works

Summary

- We are developing Hybrid Motion Simulator
- 1-DOF Hybrid Motion Simulator is feasible
- HEXA-X2 is under development for Hybrid Flight Simulator

Future Works

- Get the flight data from R/C model
  → Model position, attitude, velocity (IMU, GPS)
- Wind tunnel testing
- Validation of Hybrid flight simulation
- Visualization
Thank you for your attentions!
Significance of Hybrid Flight Simulator

■ The simulation in an actual phenomenon
  • The power from a fluid phenomenon is measured using a physical model

■ The action of an aircraft is reproducible
  • The Hybrid Motion Simulator can reproduce an action, unlike a compulsive shaking test

■ A dangerous action is safely reproducible
  • Since the aircraft is moved using a robot manipulator, there no worries about crash and contact which may take place by actual flight
Flight Test (2)

- **R/C model**
  - Propeller model

- **EDF (Electric Duct fan) model**

- **Get Flight Data**
  - Model Position
  - Model attitude
  - Velocity

Gathering data from IMU & GPS

- Length: 682 [mm]
- Span: 480 [mm]

- Length: 675 [mm]
- Span: 520 [mm]
Flow Visualization for dynamic model (1)

- Laser light sheet method
  - Flow phenomena upper the model can be visualized
Flow Visualization for dynamic model (2)

**PSP (Pressure Sensitive Paint)**
- PSP is a pressure distribution sensor
- Pressure field on the model can be visualized

\[ \phi = 0 \text{ [deg]} \quad \phi = 10 \text{ [deg]} \quad \phi = 20 \text{ [deg]} \]
Flow Visualization for dynamic model (3)

- **Fluorescence minituft method**
  - Fluorescence monofilaments are glued to the model surface
  - Flow direction and unsteady region on the model surface can be visualized

0 [deg]
Phase lead compensation

- PLC for the sensor delay
  - Identifies from the Bode diagram of a force/torque sensor

\[ G(s) = e^{-Ls} \]

The transfer function of a dead time element

Bode diagram

Curve fitting by a dead time element

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Phase lead compensation

■ PLC for the sensor delay
  • Identifies from the Bode diagram of a force/torque sensor

\[ G(s) = e^{-Ls} \]

The transfer function of a dead time element

Approximation by a dead time element
Phase lead compensation

- The PLC result of sensor delay

Rolling moment coefficient

Angular acceleration

Limit cycle
Unmanned Aerial Vehicle
UAVs developed in Uchiyama Lab.

Quad rotor UAV

Tail-sitter UAV

CCV
Tail-Sitter VTOL UAV

Advantages:
• Long range flight performance
• Simple mechanism

Disadvantages:
• Difficulty in canceling rotor reaction moment in vertical mode
Transition from Level Flight to Hovering
Transition from Hovering to Level Flight

Hovering

[Graph showing transition from hovering to level flight with data on altitude and pitch angle over time and position]

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Trajectory Tracking in Hover Mode
Post-stall Maneuver: Minimum distance turn
Post-stall Maneuver: Constant altitude turn
CCV (Control Configured Vehicle)

**Advantages:**
- Turn without rolling
- Ultralow flying

**Disadvantage:**
- Computer assist is absolutely imperative

Turn of general airplane

- With rolling movement
- Without rolling movement

Turn of CCV

- Vertical canard
Lateral Translation Flight
Free-Floating Space Robot

When the robot arm moves, the reaction force affects the attitude of the satellite.
Hardware-in-the-loop Simulator

- Simulation on Ground for Space Application
- Precise Reproduction of Complicated Physical Phenomena
Problem in Hardware-in-the-loop Simulation

Time delay exists due to servo delay and low pass filter

Energy Increase during contact or impact

Instability of the system and unrealistic physical phenomena

Delay time compensation based on the coefficient of restitution
Experimental Setup and Wind Tunnel

- **Low-Turbulence Heat-Transfer Wind Tunnel @Tohoku Univ.**

  Model: Single-path return-flow type  
  Measurement section: open  
  2nd nozzle opposite side distance: 0.81m  
  Length: 1.42 m  
  Flow speed: 5–70 m/s

- **Scaled airplane model: Delta Wing**

  Sweepback angle: 80 [°]  
  Chord length: 300 [mm]  
  Thickness: 2 [mm]  
  Leading edge: 45 [°] sharp edge  
  Material: A2017 (Duralmin)
System Configuration

Physical Model → F/T Sensor → Numerical Model

Dynamics Calculation

\[ F = m \ddot{x} \]
\[ M = I \ddot{\theta} \]

Manipulator:

Servo Mechanism

Motion Demonstration
Verification of Hybrid Motion Simulator

Aerodynamic phenomena in uniaxis

- Wing Rock
- Damped Vibrations

Conventional Method
Free motion around one axis by using bearing

Comparison

Nondimensional Frequency
(Strouhal Number)

Proposed Method
Motion demonstrated by manipulator system

Wing Rock Phenomena
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Damped Vibration Motion
demonstrated by Hybrid Motion Simulation

Workshop on Next Generation Transport Aircraft
Flight Test (2)

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