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

MPM(DNW)

Dutch Roll Motion

EFD + Flight Dynamics = Hybrid Motion Simulation
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

Numerical model

Physical model
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)

Experimental model
  Servo mechanism
  Model positioning

Numerical model
  Dynamics calculation
  position and attitude

Force and Torque (F/T) Sensor
  Measuring force and torque
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]
  
\( f=3.2 \) [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]

\[f=1.15\] [Hz]

Need to increase the accuracy

Rolling motion device

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

2013/3/29
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]

\[
K \frac{T s + 1}{\alpha T s + 1}
\]

\( f = 1.95 \) [Hz]

Compensate for other delays

Hybrid Motion Simulation (PLC)
Multi-DOF Hybrid Motion Simulation

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

Get flight data from R/C model

Hybrid Motion Simulation

Numerical model
- Evaluate model position & attitude
- Dynamics simulation

Experimental model
- Exercise experimental model
- Measure aerodynamic force
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
  • HEXA-X2 is a Parallel link robot manipulator

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

Dutch Roll Motion (3Hz)

PA-10 (Serial Robot)  HEXA-X2 (Parallel Robot)

High-output geared motors
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

Hybrid Flight Simulator
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**
  length: 675 [mm]
  span: 520 [mm]

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

Gathering data from IMU & GPS
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

Curve fitting by a dead time element

Bode diagram
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

**Limit cycle**

**Rolling moment coefficient**

**Angular acceleration**
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

Level Flight

![Diagram showing transition from level flight to hovering with graphs indicating altitude and pitch angle changes over horizontal position and time.](image)

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Transition from Hovering to Level Flight

Hovering

Graphs showing altitude and pitch angle over horizontal position and time.
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
- With rolling movement
- Without rolling movement

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: 0.81 m
  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 Phanomena
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Damped Vibration Motion demonstrated by Hybrid Motion Simulation
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]