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

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

■ Hybrid Flight Simulation

Contact phenomena  ➔ Aerodynamic phenomena

New application

Numerical model

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

■ 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

Rolling motion device
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

**Hybrid Motion Simulation**
- Get flight data from R/C model
- Calculate the flight dynamics and obtain data
- Demonstrate the unsteady motion using by robot
- Measuring aerodynamic force and torque

**Experimental model**
- R/C model
- Wind-tunnel
- Robot manipulator

**Numerical model**
- Calculate the flight dynamics and obtain data

**Force and Torque sensor**
- Measuring aerodynamic force and torque
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

Dutch Roll Motion (3Hz)

High-output geared motors

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%

- **Electronics system**
  - IMU measure the model’s attitude, acceleration and velocity

<table>
<thead>
<tr>
<th>Model</th>
<th>Mini JAS-39 Gripen EDF Fighter Jet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length [mm]</td>
<td>700</td>
</tr>
<tr>
<td>Wing chord [mm]</td>
<td>300</td>
</tr>
<tr>
<td>Wing span [mm]</td>
<td>510</td>
</tr>
<tr>
<td>Sweep angle [deg]</td>
<td>55</td>
</tr>
<tr>
<td>Weight [g]</td>
<td>360</td>
</tr>
</tbody>
</table>

Mini JAS-39 Gripen EDF Fighter Jet

On-board electronics system

- Throttle
- Logging data
- Motor controllers
- Electric current
- Interface board & Computer
- Acceleration Angular velocity
- Mode switch
- RC transmitter
- MicroSD module
- Attitude sensor
- Servo motor for wings
- RC receiver
- Command

2013/10/15
2012-13 Boeing Higher Education Student Project Presentation
Numerical Calculation

■ Equation of motion
  - Translation
    \[ m\ddot{V} + m(\omega \times V) = F \]
  - Rotation
    \[ I\ddot{\omega} + \omega \times I\omega = G \]

  \( M \) : Mass
  \( I \) : Inertia tensor
  \( F \) : Force
  \( G \) : Torque
  \( V \) : Velocity
  \( \omega \) : Angular velocity

■ Calculate model’s position and attitude
  - The position and attitude of the model are calculated by integrating acceleration and angular acceleration.

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Force & Torque \[\rightarrow\] Equation of motion \[\rightarrow\] Acceleration & Angular acceleration

Acceleration & Angular acceleration \[\rightarrow\] Velocity & Angular velocity \[\rightarrow\] 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

<table>
<thead>
<tr>
<th>Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind velocity [m/s]</td>
<td>10</td>
</tr>
<tr>
<td>AoA [deg]</td>
<td>10, 20, 30, 40</td>
</tr>
<tr>
<td>Oscillation Frequency [Hz]</td>
<td>0.5, 1.0, 1.5</td>
</tr>
<tr>
<td>EDF Thrust [%]</td>
<td>100</td>
</tr>
</tbody>
</table>
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).

\[ f = 4\text{Hz}, \Delta \phi = 10\text{deg} \]
This result indicates that while the angle of attack is increased, the amplitude is increased and the symmetry of hysteresis loop is broken.
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.

<table>
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<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmospheric pressure [hPa]</td>
<td>1019.82</td>
</tr>
<tr>
<td>Wind velocity [m/s]</td>
<td>1.93</td>
</tr>
<tr>
<td>Temperature [degC]</td>
<td>22.2</td>
</tr>
<tr>
<td>Model weight [g]</td>
<td>360</td>
</tr>
<tr>
<td>Battery capacity [mAh]</td>
<td>550</td>
</tr>
</tbody>
</table>
Result of Flight Testing
Result of Flight Testing
Analysis of Unsteady Behavior

- 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

- 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.
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.
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.

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</thead>
<tbody>
<tr>
<td>Angle of attack [deg]</td>
<td>15</td>
</tr>
<tr>
<td>Wind velocity [m/s]</td>
<td>10</td>
</tr>
</tbody>
</table>
Result of HMS

- 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!