Development of Dynamic Wind Tunnel Test Using 1-m Magnetic Suspension and Balance System

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Aiming for Safety Flight

Fatalities by CICTT Aviation Occurrence Categories
Fatal Accidents | Worldwide Commercial Jet Fleet | 2008 through 2017

LOC-I : Loss Of Control-In flight
Cannot recover from an abnormal flight condition

Note: Principal categories as assigned by CAST.
For a complete description of CAST/ICAO Common Taxonomy Team (CICTT) Aviation Occurrence Categories, go to www.intlaviationstandards.org.

The Boeing Company, 2018.

2019.1.21 Boeing Higher Education Program Debriefing Meeting
Modeling the extreme flight condition

= Near or outside of the edge of the flight envelope

Unsteady aerodynamics affect the flight characteristics

NASA Langley (from YouTube), 1960.

Kroll N. et al., 2012.
How to Understand Unsteady Aerodynamics

Issues of dynamic wind tunnel

1. Complicated support mechanism or limit the motion degrees-of-freedom

2. Interference with flow stream or apply the correction (very hard)

MSBS: Magnetic Suspension and Balance System

MSBS can perform the wind tunnel tests without mechanical interference


1-m MSBS : The largest MSBS in the world

Position sensor

Model
Contains permanent magnets

Control PC with feed-back control system

Coil

- 1m (Tohoku)
- 0.1m (Tohoku)
- MIT/NASA Langley
- U. of Southampton
- AEDC/NASA Langley
- JAXA
What function is required?

1. Make a motion
   - Considering a simple forced-oscillation test

2. Measure an unsteady aerodynamic force
   - Validating with inertial force

\[ N = J \frac{d^2 \theta}{dt^2} \]

Inertial torque

\( \theta(t) \)
Goal of the study

Our goal

Performing a dynamic wind tunnel test using 1-m MSBS

- Evaluation of the motion accuracy
- Validation of the force evaluation accuracy
- Dynamic wind tunnel at simple flight condition
- Dynamic wind tunnel at extreme flight condition
Goal of the study

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Motion Accuracy

How to excite the model:

The motion was unstable
How to excite the model:

- Motion command
- PC
- Current command
- Coils
- Magnetic force
- Model

Noisy wave

Sinusoidal wave + noise

Decided by feed-back control with phase delay

Input this “bias” signal as a sinusoidal function with phase advance

Input by feed-back control with minimum amplitude
Motion Accuracy

NON excited direction ($z$)

Excited direction ($\theta$)

25 m/s

Angles of attack error < 0.005 degrees
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Force Measurement Accuracy

How to measure the aerodynamic force:

\[ N = \left( I_{\text{wind-on}} - I_{\text{wind-off}} \right) \times C \]

- \( N \): Aerodynamic moment
- \( I_{\text{wind-on}} \): Coil current
- \( I_{\text{wind-off}} \): Coil current
- \( C \): Coefficient

\[ N_y = C_{\text{pitch}} I_{\text{pitch}} \]

- \( N_y \): Gain change
- \( C_{\text{pitch}} \): Phase delay

\[ N_y(t) = \alpha C_{\text{pitch}} I_{\text{pitch}}(t + \tau) \]
Force Measurement Accuracy

Validation with Inertial torque

Coil current and inertial torque (4Hz)

\[ \Delta N_y [\text{Nm}] \]

<table>
<thead>
<tr>
<th>Amplitude [degree]</th>
<th>Phase lag [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>180</td>
</tr>
<tr>
<td>1</td>
<td>181</td>
</tr>
<tr>
<td>2</td>
<td>182</td>
</tr>
<tr>
<td>3</td>
<td>180</td>
</tr>
<tr>
<td>4</td>
<td>179</td>
</tr>
</tbody>
</table>

Theoretical value from motion wave

Theoretical value : 180 deg

Maximum error amplitude : 2.4 %

phase lag : 0.1 degree
Goal of the study

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- Dynamic wind tunnel at extreme flight condition
Wind tunnel in simple flight condition

Test condition

AGARD-B winged model

3, 4, 5 Hz

1 degree

25 m/s

<table>
<thead>
<tr>
<th>Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oscillatory direction</td>
<td>pitch</td>
</tr>
<tr>
<td>Free stream velocity [m/s]</td>
<td>25</td>
</tr>
<tr>
<td>Reynolds number (based on m.a.c.)</td>
<td>$2.9 \times 10^5$</td>
</tr>
<tr>
<td>Oscillation frequency [Hz]</td>
<td>3, 4, 5</td>
</tr>
<tr>
<td>Oscillation center AoA [deg]</td>
<td>0.0</td>
</tr>
<tr>
<td>Oscillation amplitude [deg]</td>
<td>1.0</td>
</tr>
<tr>
<td>Reduced Frequency</td>
<td>0.065 ~ 0.109</td>
</tr>
</tbody>
</table>

Evaluated flight parameter

Measurement object:

Motion

Aerodynamic moment

$\theta(t) = \theta_0 \sin(2\pi ft)$

$N_y(t) = N_{y0} \sin(2\pi ft + \tau)$

Stability derivatives:

Static stability

(Also obtained by static test)

Dynamic stability

$C_{m\alpha}$

$C_{m\alpha} + C_{mq}$
### Stability derivatives evaluation

<table>
<thead>
<tr>
<th>Condition</th>
<th>$C_{m\alpha}$ [/deg]</th>
<th>$C_{m\alpha} + C_{mq}$ [/rad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 Hz</td>
<td>0.010 $\pm$ 0.000</td>
<td>-0.9 $\pm$ 0.5</td>
</tr>
<tr>
<td>4 Hz</td>
<td>0.010 $\pm$ 0.000</td>
<td>-0.8 $\pm$ 0.2</td>
</tr>
<tr>
<td>5 Hz</td>
<td>0.010 $\pm$ 0.000</td>
<td>-1.0 $\pm$ 0.1</td>
</tr>
<tr>
<td>Static</td>
<td>0.010 $\pm$ 0.000</td>
<td>-</td>
</tr>
<tr>
<td>DATCOM</td>
<td>0.008</td>
<td>-1.1</td>
</tr>
</tbody>
</table>

DATCOM: a computer-based evaluation

1. **Static stability agreed well between dynamic and static tests**
   - The dynamic wind tunnel was performed appropriately

2. **Dynamic stability approximately agreed each other**
   - Aerodynamic stability evaluation in unsteady flight condition is available
Future plan suggestion

- Evaluation of the motion accuracy
- Validation of the force evaluation accuracy
- Dynamic wind tunnel at simple flight condition
- Dynamic wind tunnel at extreme flight condition

Future plan suggestion

Issues to make this study practical

1. Perform the dynamic wind tunnel with:
   a) High angles of attack
   b) Large amplitude and frequency

2. Upgrade the model to lightweight

3. Perform the test with realistic shaped model
Summary

Development of dynamic wind tunnel technique using 1-m MSBS:

**Motion accuracy**
- Error of AoA: within 0.005 deg

**Unsteady force evaluation accuracy**
- Error of evaluation: within 2.4% in amplitude, 0.1 degree in phase

**Dynamic wind tunnel**
- Evaluated dynamic stability agreed well with estimated value

Unsteady aerodynamic measurements using 1-m MSBS are feasible.

Thank you for listening!