Numerical Simulation of Flow Field around an Inflatable Vehicle during a Reentry Demonstration Flight considering Membrane Deformation

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• Membrane deformation
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- Reduce entry-velocity with low ballistic coefficient flight
- Reduce heat flux by deceleration at high altitude
- It can land softly without a parachute system
SMAAC (Sounding rocket experiment of Membrane Aeroshell for Atmospheric-entry Capsule)

Experimental Vehicle

- **<Inflatable torus frame>**
  - Made of Silicone rubber sheet and ZYLON textile
  - Torus tube diameter: 10cm, Torus outer diameter: 120cm, Mass: 2kg

- **<Thin membrane flare>**
  - Made of ZYLON textile.
  - Flare angle: 70 deg, outer diameter: 100cm, Mass: 0.7kg

- **<Capsule (Main body)>**
  - Hemispherical head and cuboidal body.
  - Diameter: 228mm, Length: 540mm, Mass: 13kg
  - All of the electrical device and gas injection system are installed
**Flight test**

**Test sequence**

1. Aeroshell is packed around the capsule when launching.

2. Nose cone opens after rocket engine burn out.

3. When aeroshell cover is released and gas is injected into the torus, The aeroshell was deployed.

4. Experimental vehicle was ejected from rocket by separation mechanism.

5. Experimental vehicle reenter to atmosphere with large angle of attack.

6. Aeroshell shape and vehicle attitude become stable by aerodynamic force.

7. At altitude from 75km to 45km
   - Maximum Mach number: 4.6
   - Maximum heat flux: 16.5kW/m²
   - Maximum dynamic pressure: 0.5kPa

8. Vehicle splashes down with 15.3m/s in 1150 sec after top of trajectory.

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S310-rocket (ISAS)
## Previous research

Ha, Dongheun, et al.
"Numerical Simulation of Flow Field around an Inflatable Vehicle during a Reentry Demonstration Flight."
32nd AIAA Applied Aerodynamics Conference, 2014

<table>
<thead>
<tr>
<th>Case</th>
<th>Flight model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude, km</td>
<td>58 54 47 43 40 39 37</td>
</tr>
<tr>
<td>Velocity, m/sec</td>
<td>1249.5 1127.6 749.7 485.7 315.2 276.3 225.8</td>
</tr>
<tr>
<td>Temperature, K</td>
<td>248.3 257.3 263.0 258.6 252.6 250.1 245.1</td>
</tr>
<tr>
<td>Density, kg/m3</td>
<td>4.24e-4 6.95e-4 1.67e-3 2.84e-3 4.25e-3 4.97e-3 6.67e-3</td>
</tr>
<tr>
<td>Mach number</td>
<td>3.95e0 3.50e0 2.30e0 1.51e0 1.00e0 8.71e-1 7.19e-1</td>
</tr>
<tr>
<td>Reynolds number</td>
<td>3.98e4 5.72e4 9.01e4 1.00e5 9.94e4 1.03e5 1.14e5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Case</th>
<th>Flight model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude, km</td>
<td>35 30 20 10 5.0 3.0 1.0</td>
</tr>
<tr>
<td>Velocity, m/sec</td>
<td>189.0 122.1 53.1 25.6 21.3 18.4 16.5</td>
</tr>
<tr>
<td>Temperature, K</td>
<td>240.3 229.4 209.6 242.4 274.4 285.0 295.6</td>
</tr>
<tr>
<td>Density, kg/m3</td>
<td>8.99e-3 1.91e-2 9.81e-2 4.17e-1 7.11e-1 8.71e-1 1.06e0</td>
</tr>
<tr>
<td>Mach number</td>
<td>6.08e-1 4.02e-1 1.83e-1 8.20e-2 6.40e-2 5.43e-2 4.77e-2</td>
</tr>
<tr>
<td>Reynolds number</td>
<td>1.31e5 1.87e5 4.50e5 8.18e5 1.05e6 1.08e6 1.14e6</td>
</tr>
</tbody>
</table>
Previous research

\[ C_D = \frac{qS}{ma} \]

- \( q \): dynamic pressure
- \( S \): characteristic area
- \( m \): mass of vehicle
- \( a \): acceleration

Mach number

Altitude, km

Drag coefficient (Flight)

Drag coefficient (FaSTAR)

Drag coefficient (FFR)

Supersonic region

Transonic region

Subsonic region

Altitude, km

0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2

0 10 20 30 40 50 60 70 80 90 100

7
Previous results

Simulation model used previous research

This model was assumed as a rigid body

There is a difference between these models

Real model is made of fabric, and it is deformed by aerodynamic force

figure of wind tunnel test
Objective

Post analysis is important for future experiment

It is necessary to validate numerical simulation method

Investigate the influence of membrane deformation by using numerical simulation.
Membrane deformation


\[ \rho S_0 \frac{d^2 r}{dt^2} = F_E + F_A \]

\[ F_E = F_T + F_S + F_B \]

- \( F_E \): elastic force
- \( F_A \): aerodynamic force
- \( F_T \): tension force
- \( F_S \): shear force
- \( F_B \): bending force

Aerodynamic schematic
Previous research

Takahashi Y., et. al
“Preliminary Study for Fluid-Structure Problem of Membrane Deformation using Virtual Particle Method” SSW-2c1-3, 2014

Pressure coefficient profiles along SMAAC surface (altitude of 43 km).

(a) Initial (AOA 0 degree).
Computation process

Initial shape

Fluid simulation

Membrane deformation

Fluid simulation with deform model
Numerical setting – Membrane deformation -

- **Boundary conditions**

- **Number of elements**
  : $120 \times 239$ structure grids

- **Time integration**
  : $4^{th}$ Runge-Kutta
### Numerical setting – FFR and FaSTAR

<table>
<thead>
<tr>
<th>Software package</th>
<th>Front Flow Red 3.1</th>
<th>RG-FaSTAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discretization</td>
<td>Vertex-centered finite volume method</td>
<td>Cell-centered finite volume method</td>
</tr>
<tr>
<td>Numerical fluxes</td>
<td>Convection term: 2(^{nd}) order central difference scheme (95%) and 1(^{st}) order upwind scheme (5%), and Viscous term: 2(^{nd}) order central difference scheme</td>
<td>Convection term: SLAU((+)MUSCL interpolation), and Viscous term: 2(^{nd}) order central difference scheme</td>
</tr>
<tr>
<td>Time-marching method</td>
<td>SMAC-type implicit method (using Crank-Nicolson method)</td>
<td>Implicit method (Euler Implicit)</td>
</tr>
<tr>
<td>Poisson equation solver</td>
<td>ICCG method</td>
<td>-</td>
</tr>
<tr>
<td>Turbulence model</td>
<td>LES, standard Smagorinsky model ((C_{S}=0.15))</td>
<td>RANS: SST</td>
</tr>
<tr>
<td>Molecular viscosity</td>
<td></td>
<td>Sutherland’s law</td>
</tr>
<tr>
<td>Parallel computing</td>
<td></td>
<td>MPI</td>
</tr>
<tr>
<td>Time step</td>
<td>5.0x10(^{-6})sec/step</td>
<td>-</td>
</tr>
</tbody>
</table>
Results – altitude of 37km –
Results – altitude of 37km-

Distribution of pressure coefficient

Distribution of pressure coefficient (with deformation)

<table>
<thead>
<tr>
<th>x, m</th>
<th>Cp</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.5</td>
<td>-1.5</td>
</tr>
<tr>
<td>0</td>
<td>-0.5</td>
</tr>
<tr>
<td>0.5</td>
<td>-0.5</td>
</tr>
</tbody>
</table>

Initial model
Deformed model
Results – altitude of 54km –
Results – altitude of 54km -

Distribution of pressure coefficient (initial model)

Distribution of pressure coefficient (with deformation)
Results

Altitude of 37km

<table>
<thead>
<tr>
<th>Altitude, km</th>
<th>37km</th>
<th>54</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deformation</td>
<td>Without</td>
<td>With</td>
</tr>
<tr>
<td>Drag force</td>
<td>192.682</td>
<td>177.877</td>
</tr>
<tr>
<td>Cd</td>
<td>1.0</td>
<td>0.92</td>
</tr>
</tbody>
</table>
Conclusion

☐ In this research, we simulated deformed models at the altitude of 37km and 54km

☐ In the case of altitude of 37km, there was a difference of drag coefficient between considering membrane deformation model and initial model and it is considered by pressure distribution at the torus

☐ In the case of altitude of 54km, Although there was a difference of distribution of surface pressure coefficient, there was little difference of drag coefficient

☐ We plan to simulate more deformed models through all of speed range
Thank you for your kind attention