Computational Fluid Dynamics Study of Balloon System Tethered to a Stratosail

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Outline

• Introduction of StratoSail

• Computational Modeling of Balloon-StratoSail System

• Results on Drift Velocity and Tether Length

• Conclusion and Future Work
Station-Keeping of Stratospheric Balloon

- Within 2 km horizontal radius
- Over a one-week duration
- Altitude of between 20 km and 30 km
- A minimum payload capacity of 200 kg
Wind Speed at Various Altitudes

The wind speed vs altitude [Cees Bil, 2014]
1.0 feet=0.3048 m, 1.0 mph=0.447m/s

- Balloons drift with local wind.
- Wind direction changes with altitude.
- Indirect trajectory control through altitude control.

Target altitude 20km to 30km

Google loon control
NASA StratoSail – Horizontal Motion Control

- Developed by Global Aerospace Corporation (GAC)
- Used as Balloon Guidance System (BGS) for NASA
- Wing, rudder, boom, 15 km-tether
- Generate horizontal lift or drag
- 1m/s velocity correction capability
- Successful ¼ scale ground test in 1999

Objectives and Scope

- **To develop a computational model**
  - Calculate the drag force on stratosail
  - Determine the drift velocity of balloon-stratosail system
  - Parametric study on balloon size, angle of attack, and altitudes
  - Determine the tether length

- **Simplifications**
  - 2D analysis
  - Steady-state: dynamic equilibrium
  - Best case scenario of opposing winds
Our Numerical Model

Rudder: 8ft by 2 ft
Wing: 18ft by 3.6 ft
Aluminium boom: 20 ft
Atmospheric Properties

Plot of altitude (km) against Wind Speed (m/s) (Struzak, 2003)


<table>
<thead>
<tr>
<th>Property</th>
<th>45</th>
<th>40</th>
<th>30</th>
<th>15</th>
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<tbody>
<tr>
<td>Height Of Stratosphere (km)</td>
<td>45</td>
<td>40</td>
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<td>15</td>
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<tr>
<td>Temperature of air (K)</td>
<td>265.05</td>
<td>251.05</td>
<td>226.65</td>
<td>216.65</td>
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<td>Air Density (kg/m$^3$)</td>
<td>1.88E-03</td>
<td>3.85E-03</td>
<td>1.80E-02</td>
<td>1.94E-01</td>
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<td>Wind Speed (m/s)</td>
<td>33</td>
<td>26</td>
<td>11</td>
<td>15</td>
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<tr>
<td>Kinematic Viscosity (N.s)</td>
<td>1.69E-05</td>
<td>1.62E-05</td>
<td>1.49E-05</td>
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Computational Domain

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<th>Domain Settings</th>
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<tr>
<td>Dimensions of Domain</td>
<td>200m x 100m x 300m</td>
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<tr>
<td>Volume of Stratosail</td>
<td>0.267m$^3$</td>
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<tr>
<td>Ratio of Volume of Domain over Volume of Stratosail</td>
<td>2.25E+07</td>
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<th>Fluent Settings</th>
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<td>Viscous Model</td>
<td>SST K-Omega</td>
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<td>Stratosail Boundary Condition</td>
<td>No-Slip Wall Condition</td>
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<td>Inlet Boundary Condition</td>
<td>Velocity-Inlet</td>
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<td>Outlet Boundary Condition</td>
<td>Outflow</td>
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<td>Surrounding Walls</td>
<td>Gauge Pressure=0</td>
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<td>Inflation Option</td>
<td>Smooth Transition</td>
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<th>Angle of Attack</th>
<th>Nodes</th>
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<tr>
<td>0 degrees</td>
<td>77208</td>
<td>403512</td>
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<tr>
<td>30 degrees</td>
<td>77329</td>
<td>403376</td>
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<tr>
<td>60 degrees</td>
<td>76948</td>
<td>401424</td>
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<tr>
<td>90 degrees</td>
<td>78130</td>
<td>406841</td>
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Solve for Drift Velocity by Iteration

1. Assume Drift Velocity, \( V_d \)
2. Calculate Relative Speed of wind on stratosail
3. Calculate Drag Force on Stratosail
4. Calculate Relative Speed of Wind on Balloon
5. Calculate Drag Force on balloon
6. Are the two Drag Forces Equal?
   - Yes: Assumed Drift Velocity is correct
   - No: Perform Another Iteration
Centenary Cable

Calculate the tether length to maintain steady-state drift motion at fixed altitudes.

\[ y = \frac{T_0}{w} \cosh \left( \frac{wz}{T_0} \right) \]

\[ s = \frac{T_0}{w} \sinh \left( \frac{wz}{T_0} \right) \]
Validation of CFD simulation

- Drag force/coefficient on a sphere at various speeds (Reynold’s No.)
- Fluent software simulation close to reported data
- Small differences noticed with inflation option turned on to smoothen the transition of elements
Drag Force on Stratosail

- Stratosail at 15 km altitude
- Drag force is larger at angle of attack of 90° compared to 60°
- Frontal area decreases with angle of attack
Drift velocity of Balloon-Stratosail System

- Wind speed at balloon altitude 30km: 12.5 m/s
- Drift velocity: less than 2 m/s for various sizes of the balloon for stratosail at 15km
- Drift velocity increases with balloon size

- Drift velocity increases to about 10 m/s with stratosail moved to 20 km and 25 km due to lower wind speed at those altitudes.
Drift velocity decreases when the angle of attack is reduced from 90° to 60° due to the reduction in drag force.
Tether Length for Various Cases

- Length of tether for various cases of altitudes and angle of attack
- Length increases with size of balloon due to larger drag force (parameter $T_0$)
- Angle of attack at 90° gives larger tether length than 60°
- Changing the tether length will change the dynamics of the system
Conclusion and Future Work

- Preliminary work on simulation of balloon-stratosail system
- Drift velocity: Feasibility of station-keeping

Future work
- Full 3D and transient motion simulation
- Use of more realistic wind-speed data, especially wind directions
- Change of tether length and stratosail angle of attack as control parameters
- Evaluate control strategies for station-keeping by using the stratosail (or with other active means)
THE END