Aerodynamic instability of flare-type membrane inflatable vehicle in suborbital reentry demonstration

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Abstract
An inflatable membrane reentry vehicle has been developed as one of the innovative reentry technologies. A suborbital reentry demonstration using a sounding rocket was carried out in 2012. Contrary to the result of a preliminary study, the vehicle always had an angle of attack (AoA) during its reentry. In addition, the amplitude of AoA gradually increased as altitude decreased, and the vehicle rotated vertically under Mach number of 0.1 (M0.1). As a first step to clarify the cause of attitude instability and vertical rotation, the aerodynamic characteristics, that concern static stability, are numerically investigated. Numerical simulations were carried out for the cases of Mach 0.9 (M0.9), 0.6 (M0.6), 0.3 (M0.3) and 0.1 (M0.1) and pitching moment coefficients ($C_M$) were obtained. Analysis software “RG-FaSTAR” for M0.9, and “FrontFlow/red” for M0.6, M0.3 and M0.1, are used, respectively. Large eddy simulation (LES) was performed using the standard Smagorinsky model to resolve highly unsteady flow features. Because the slope of $C_M$ with respect to AoA was negative for all cases, it was found that the vehicle is statically stable. For M0.9, M0.6 and M0.3 cases, absolute values of $C_M$ were almost the same. On the other hand, for M0.1, $C_M$ had a particularly large value, because the surface pressure distribution on rear side of the vehicle was different from the other cases. This difference was attributed to the separation point on the lower torus moving backward and turbulence in wake being enhanced with a decrease in Mach number and an increase in the Reynolds number.

Keywords: Thin-membrane inflatable aeroshell, Suborbital reentry, Static stability, Large eddy simulation

1. Introduction

Inflatable aeroshell has been developed as one of the innovative reentry technologies. The main advantage of these types of vehicles is the low ballistic coefficient during reentry. Since then, several studies and demonstration flights have been carried out by the National Aeronautics and Space Administration (NASA), the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA). Inflatable reentry vehicles can decelerate at a higher altitude compared with conventional rigid reentry vehicles, which provide several advantages during entry, descend and landing (EDL), such as a reduction in aerodynamic heating.

For a flare-type thin-membrane inflatable aeroshell, several studies have been performed with elemental technologies and demonstration flights, as part of the membrane aeroshell for atmospheric-entry capsule (MAAC) project, by cooperation with several universities and JAXA. This type of reentry vehicle, having the form of a capsule with a tightly packed aeroshell, e.g., a slender cylindrical shape, is firstly transported to an orbit. As the torus tube inflates under vacuum and microgravity environment on the orbit, the membrane aeroshell rapidly expands. After deployment, the membrane aeroshell is sustained by the inflatable torus. Because of the large area and the light weight of the membrane aeroshell deployed, efficient aero-deceleration at a high altitude becomes possible, leading to a reduction in aerodynamic heating during atmospheric reentry. Note that the aeroshell also plays the roles of a parachute and a float in the descent phase and during landing/splashing down. In addition, because deployment of the aeroshell is carried out before deorbiting, it is possible to avoid critical and difficult operation in parachute opening during EDL.
As an important study on MAAC project, the suborbital reentry demonstration of the sounding rocket experiment of membrane aeroshell for atmospheric-entry capsule (SMAAC) using the JAXA S-310 sounding rocket was carried out in August 2012 (Yamada et al., 2015). The purpose of this demonstration flight was to clarify the low-ballistic coefficient flight of a type of inflatable vehicle during reentry in detail. SMAAC mainly has three components: a capsule, a thin-membrane aeroshell and an inflatable torus, as shown in Fig. 1. The capsule has a semispherical configuration with a diameter of 190 mm. The membrane aeroshell has a flare angle of 70° and a frontal projected diameter of 910 mm, respectively, and is connected to the inflatable torus. The inflatable torus has a tube with a diameter of 100 mm. The overall diameter of the vehicle is 1200 mm after being inflated. Note that the diameter becomes 1250 mm when the torus is sufficiently pressurized. The primary fabric used for the aeroshell and torus is Zylon, which has a high thermal durability and high tensile strength.

![Fig. 1 Configuration of SMAAC](image)

Regarding the demonstration flight of SMAAC, the reentry trajectory was evaluated by Yamada et al. After the launch of the sounding rocket, the aeroshell cover of the vehicle was opened at an altitude of 100 km, and the inflatable torus was injected with gas at 106 km to deploy the membrane aeroshell. The vehicle separated from the rocket at 111 km. The reentry of SMAAC started at an altitude of 150 km. When separated from the rocket, the vehicle had an angular velocity of 1.2 Hz around the body axis (in the roll direction) to maintain the stability of the vehicle. During reentry, the Mach number reached a maximum value of 4.6, and a maximum heat flux and dynamic pressure are 16.5 kW/m² and 0.5 kPa, respectively. Finally, the vehicle splashed down with terminal velocity of 15.3 m/s.

Thus far, various aerodynamic studies have been conducted on SMAAC. Ha et al. (Ha et al., 2014a) and Takahashi et al. (Takahashi et al., 2017) investigated aerodynamic characteristics of SMAAC with a computational fluid dynamics (CFD) approach, for various cases between altitude of 58 km and 1.0 km, i.e., from a supersonic flow regime to a subsonic one. In the paper, the simulated drag coefficient showed good agreement with the measured results. It was indicated that the analytical model is sufficient for predicting flow field around the inflatable reentry vehicle. As with the measured results, the simulated drag coefficient had almost a constant value of 1.5 in the supersonic region but gradually decreased to 1.0 or less in the subsonic region with the decrease of the Mach number. In the transonic region, a steep decrease of the drag coefficient was reproduced. It was concluded that the effect of the compressibility in the shock layer in front of the vehicle in the supersonic region and the vortex ring behind the vehicle in the subsonic region are important mechanisms, that are affecting the detailed prediction of the aerodynamic coefficient. Ha et al. investigated aerodynamics of a SMAAC shape model including a comparison of pitching moments between CFD and wind tunnel tests at low speed. It was indicated that attitude of the inflatable vehicle is statically stable. In addition, Takahashi et al. (Takahashi et al., 2015) investigated aerodynamic heating of SMAAC in a supersonic flow regime.

In this SMAAC demonstration, it was assumed that the vehicle enters into the atmosphere with an angle of attack (AoA) of 0 degree and its attitude is always stable. Nagata et al. (Nagata et al., 2013) estimated the attitude stability of SMAAC by the pitching moment coefficient obtained using the Newtonian impact theory. It was predicted that
aerodynamic stability of SMAAC is kept even if the vehicle has an AoA of 0 degree or a high AoA. However, the vehicle always had an AoA in the flight, as shown in Fig. 2. In addition, amplitude of the AoA gradually increased as altitude decreases, and the vehicle rotated vertically under the Mach number of 0.1 (M0.1). Thus, the attitude of SMAAC was unstable.

![Time history data of angle of attack, Mach number and Altitude in suborbital reentry demonstration](image)

**Fig. 2** Time history data of angle of attack, Mach number and Altitude in suborbital reentry demonstration

To prevent a decrease in aerodynamic performance of the vehicle, it is necessary to clarify the mechanisms of the attitude instability, i.e., static and dynamic instabilities. A static stability is defined as that in which the force and moment act in the appropriate direction to return to the original balancing position when the vehicle’s attitude changes. Static stability is only whether or not the restoring force or moment act to return to the original position. On the other hand, with respect to dynamic stability, not only the restoring force and moment work, but also it is necessary to actually return to the original position. In other words, for dynamic stability, the attitude motion must converge without divergence. Determination of dynamic stability needs to satisfy stricter conditions than static stability. It is difficult to investigate dynamic stability in detail and its computational cost is very high.

In this study, as a first step in investigating the reason of instability such as divergence of the attitude motion and vertical rotation observed in the demonstration, we evaluate static aerodynamic stability of the vehicle and clarify the mechanisms at the transonic and subsonic flow regions using CFD approach.

### 2. Computational methods

To evaluate static stability, numerical simulations were carried out for cases of transonic flow region at Mach number of 0.9 (M0.9) and subsonic region at Mach numbers of 0.6 (M0.6), 0.3 (M0.3) and 0.1 (M0.1).

In this study, the flow is assumed to be continuous and turbulent. The flow field is described by the Navier–Stokes (NS) equations and the equation of state. The NS equations are composed of equations for the total mass, momentums, and total energy. The NS equations can be expressed as follows:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_j}{\partial x_j} = 0 \tag{1}
\]

\[
\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} \tag{2}
\]
\[
\frac{\partial E}{\partial t} + \frac{\partial (E + p)u_j}{\partial x_j} = \frac{\partial u_i \tau_{ij}}{\partial x_j} + \frac{\partial q_j}{\partial x_j}
\]  

where \( \rho \), \( u \), \( p \) and \( E \) are the density, velocity, pressure and total energy, respectively. Additionally, \( \delta_{ij} \) is the Kronecker delta, and the stress tensor \( \tau_{ij} \) and the heat flux \( q_j \) are given by

\[
\tau_{ij} = (\mu + \mu_t) \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \frac{\partial u_k}{\partial x_k} \delta_{ij} \right)
\]

\[
q_j = (\lambda + \lambda_t) \frac{\partial T}{\partial x_j}
\]

where \( \mu \) and \( \mu_t \) are the viscosity and the turbulent viscosity. And \( \lambda \) and \( \lambda_t \) are the heat conductivity and the turbulent heat conductivity, respectively.

In general, as the features of transonic flow (compressible) and subsonic flow (incompressible) are largely different, it is better to use solvers suitable for each flow region. Therefore, for efficient and stable computations, density-based and pressure-based solvers are adopted for cases of the transonic and subsonic flow regions, respectively.

### 2.1 Transonic flow region (M0.9)

For the analysis in the transonic region, the compressible NS equations are used as the governing equation to describe the flow field. For analysis code, RG-FaSTAR (version 2.1.0) (Takahashi, 2016), developed by JAXA and Hokkaido University, is used. In the present study, large eddy simulation (LES) is carried out, and the standard Smagorinsky model is applied to a turbulence model. As a discretization method, a cell-centered finite volume approach for unstructured grids is used. Spatial gradients of flow variables at the cell are calculated, based on the Green–Gauss theorem. Numerical fluxes of the advection term of the NS equations are calculated using the SLAU scheme, and high accuracy is achieved by MUSCL interpolation method. The viscous fluxes are evaluated using the averaged gradients of the flow variables between two cells, with a correction to overcome numerical instability. The LU-SGS method is used for time integration.

### 2.2 Subsonic flow region (M0.6, M0.3, and M0.1)

For analysis in the subsonic region, low-Mach-number approximation is adopted. FrontFlow/red (version 3.1.004) (Oshima, 2009) is used as analysis code. The standard Smagorinsky model is applied to the turbulence model and LES is conducted. A cell-centered finite volume method is adopted as a discretization method. For the evaluation of numerical fluxes at cell interface, a blended scheme of 95% second-order central difference method and 5% first-order upwind method for the advection term, and second-order central difference method for the viscous term are adopted, respectively. For time integration, the Crank–Nicolson implicit scheme is used.

### 3. Computational conditions

In Fig. 3 the analytical model of SMAAIC used for the present numerical simulation is shown. Although the membrane aeroshell was deformed by aerodynamic forces during the SMAAC flight, the aeroshell is assumed to be rigid in the present computations for simplicity.

Figures 4 and 5 show the computational grids used at the transonic and subsonic speeds, respectively. For the transonic region, a triangular mesh is used in the whole computational region. The computational grids are highly clustered near the vehicle. The number of cells is approximately 36 million. For the boundary conditions of the transonic case, freestream parameters at the inflow boundary are given according to the flight data of SMAAC reentry demonstration, as listed in Table 1. At the outlet boundary, gradient-free condition is imposed on all parameters. No-slip condition for velocity is imposed on the vehicle surface. The temperature is fixed at 273 K on the vehicle surface.
For the subsonic region, triangular and pyramid meshes are used. In the region near the outlet boundary, five layers formed by triangular prism meshes of 0.2 m are inserted to stabilize the outlet condition. The number of cells is approximately 34 million. The inflow condition is given according to the flight data in a similar fashion with the transonic region. Log-law condition for the velocity is applied to the vehicle surface.

Fig. 3 Analytic model of SMAAC

Fig. 4 Computational domain and grid system near the SMAAC for transonic case

Fig. 5 Computational domain and grid system near the SMAAC for subsonic cases
4. Results

The present analysis model in the subsonic region is basically the same as in the study by Ha et al. (Ha et al., 2014b), which was validated by comparison of aerodynamic coefficient profiles versus angle of attack between CFD results and wind tunnel tests. On the other hand, the analysis model used in the transonic region is also validated based on the results by the transonic wind tunnels, although comparisons are not shown here.

The pitching moment coefficient is an important parameter in discussing the static stability. In this paper, the $C_M$ is defined to be negative when a moment acts in the direction to be recovered with an increase in AoA as shown in Fig. 6.

The $C_M$ is calculated as follows:

$$C_M = \frac{M}{\frac{1}{2} \rho_{\infty} U_{\infty}^2 S l}$$

where $M$ is the pitching moment around the center of gravity position ($0.252$ m from the tip of the vehicle), and $\rho_{\infty}$ and $U_{\infty}$ are the free-stream density and free-stream velocity, respectively. In addition, $S$ is the reference area of the vehicle ($S = \pi r^2$, where $r = 0.6$ m), and $l$ is the reference length (diameter of the vehicle = 1.2 m).

![Fig. 6 Direction relationship with the pitching moment coefficient](image)

4.1 Grid dependency

To investigate the grid dependency, we compare the value of $C_M$ obtained using the present, fine and coarse grids for the cases of AoA = 20 degrees in the transonic (M0.9) and AoA = 40 degrees in subsonic region (M0.1). The number of cells in each grid are listed in Table 2. The results of the $C_M$ and the relative error to the fine grid are listed in Table 3. The relative errors in present grid to fine grid in the $C_M$ for the all cases are within 4.14 %. However, the error in the coarse grid to the fine grid becomes larger. Especially in the case of M0.1, it is about 9.12 %. These results indicate that the present grid is sufficient for predicting the $C_M$.

Table 1 Calculation conditions

| Mach number | Reynolds number | Altitude [km] | Velocity [m/s] | Density [Kg/m$^3$] | Temperature [K] | Pressure [Pa] |
|-------------|----------------|--------------|----------------|-------------------|----------------|--------------|
| 0.9         | $1.02 \times 10^9$ | 39.3         | 286.1          | $4.76 \times 10^{-3}$ | 250.9          | $3.45 \times 10^2$ |
| 0.6         | $1.33 \times 10^9$ | 34.8         | 186.3          | $9.22 \times 10^{-3}$ | 239.9          | $6.38 \times 10^2$ |
| 0.3         | $2.61 \times 10^9$ | 26.1         | 89.8           | $3.53 \times 10^{-2}$ | 222.7          | $2.27 \times 10^3$ |
| 0.1         | $8.26 \times 10^9$ | 11.9         | 30.2           | $3.37 \times 10^{-1}$ | 227.4          | $2.21 \times 10^4$ |
### Table 2 Number of cells for the transonic region and subsonic region

|                      | Number of cells |
|----------------------|-----------------|
|                      | Fine grid       | Present grid | Coarse grid |
| Transonic region (M0.9) | 56,662,868      | 35,637,394   | 17,121,706  |
| Subsonic region (M0.1)  | 55,870,145      | 34,405,450   | 18,539,413  |

### Table 3 Pitching moment coefficient comparison for the transonic and subsonic region for each grid case

|                      | $C_M$           |
|----------------------|-----------------|
|                      | Fine grid       | Present grid (Error, %) | Coarse grid (Error, %) |
| Transonic region (M0.9) | -0.0308        | -0.0295 (4.14) | -0.0324 (5.18) |
| Subsonic region (M0.1)  | -0.0939        | -0.0947 (0.924) | -0.1024 (9.12) |

#### 4.2 Mechanism of static stability

Time-averaged values of $C_M$ obtained by the present simulations, are shown in Fig. 7. For all the Mach number cases, the gradient of the $C_M$ with respect to AoA is negative and the vehicle is found to be statically stable. For the M0.9, M0.6, and M0.3 cases, the absolute values of $C_M$ are similar. On the other hand, for M0.1, $C_M$ has a particularly large value.

The pressure coefficient ($C_p$) distribution on the SMAAC surface is shown in Fig. 8. The black solid line represents the shape of the vehicle. For the result of the M0.3 case, the $C_p$ on the rear side has a flat distribution, and the dependency on the AoA is small. Because the influence of the rear side on the pitching moment is small owing to these flat pressure distributions, the front pressure difference between the upper and bottom sides produces the negative pitching moment, which acts in the direction for reducing AoA. This is the mechanism of static stability. However, for the case of M0.1 with AoA, there also exist significant pressure differences on the rear side between the upper and bottom sides in addition to the front difference. The significant change of pressure distributions on the rear side results in a production of stronger pitching moment, leading to the rapid increase of negative $C_M$ value.

![Fig. 7 Pitching moment coefficient for all cases](image-url)
Fig. 8 Pressure coefficient distribution on the vehicle surface for AoA cases (left: M0.3, right: M0.1)

In Fig. 9, the distributions of time-averaged mainstream velocity “u” around SMAAC are shown for the M0.3 and M0.1 cases. Note that this value is normalized by the inflow velocity. As confirmed in Fig. 10, which shows an enlarged view near the lower torus of the vehicle, the separation point moves backward for M0.1 case compared to that for M0.3 cases. Moreover, from the streamline distribution in Fig. 11, turbulence in the wake is enhanced for M0.1. Because of decrease in Mach number and increase in the Reynolds number, the separation point moves backwards, and the flow attaches on the back of the capsule, with turbulence in wake being enhanced. This is the reason why the $C_p$ distributions are different between the M0.3 and M0.1 cases.

In a suborbital reentry demonstration, instabilities such as an increase in AoA and vertical rotation were observed at low Mach number, so we will conduct dynamic stability analysis to discuss further as future works.

Fig. 9 Time-averaged mainstream velocity “u” distribution normalized by freestream velocity in the case of AoA = 40° (left: M0.3, right: M0.1)

Fig. 10 Movement of separation point near the lower torus in the case of AoA = 40° (left: M0.3, right: M0.1)
5. Conclusion

To identify the causes of attitude instability and vertical rotation observed in a suborbital reentry demonstration of an inflatable reentry vehicle, aerodynamic simulations were carried out using a large eddy simulation approach at transonic and subsonic speeds. For both the transonic and subsonic regions, the results of pitching moment showed that the vehicle has the static stability in a wide range of angle of attack and for several Mach number conditions. For the case of Mach 0.1, a particularly large pitching moment was obtained, with a larger angle of attack compared to higher Mach number cases; that was attributed to the different distribution of pressure on the rear side due to the low Mach number and the high Reynolds number.

It was found that the inflatable reentry vehicle is statically stable in transonic and subsonic regions. However, this implies that the vehicle was possibly in a dynamic instability state on the demonstration flight at lower Mach number. A further discussion will be made in terms of analysis of detailed flow fields at lower Mach number condition and the dynamic stability.

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References

Ha, D., Takahashi, Y., Yamada, K., and Abe, T., Numerical simulation of flow field around an inflatable vehicle during a reentry demonstration flight, 32nd AIAA Applied Aerodynamics Conference (2014a), Paper No.2014-3283.
Ha, D., Takahashi, Y., Yamada, K., and Abe, T., Aerodynamic simulation of inflatable re-entry vehicle performance in low speed wind tunnel, TRANSACTIONS OF THE JAPAN SOCIETY FOR AERONAUTICAL AND SPACE SCIENCES, AEROSPACE TECHNOLOGY JAPAN, Vol.12, issue ists29 (2014b), pp.257-262.
Nagata, Y., Yamada, K., Abe, T., and Suzuki, K., Attitude dynamics for flare-type membrane aeroshell capsule in reentry flight experiment, AIAA Aerodynamic Decelerator Systems (ADS) Conference (2013), Paper No.2013-1285.
Oshima, N., FrontFlow/red download page (2009), available from <https://www.eng.hokudai.ac.jp/labo/fluid/download/download.htm>, (accessed on 25 March, 2018).
Takahashi, Y., Advanced validation of CFD-FDTD combined method using highly applicable solver for reentry blackout prediction, Journal of Physics D: Applied Physics, Vol.49, No.1 (2016), 015201.
Takahashi, Y., Yamada, K., Abe, T., and Suzuki, K., Aerodynamic heating around flare-type membrane inflatable vehicle in suborbital reentry demonstration flight, Journal of Spacecraft and Rockets, Vol.52, No.6 (2015), pp.1530-1541.
Takahashi, Y., Ha, D., Oshima, N., Yamada, K., Abe, T., and Suzuki, K., Aero-decelerator performance of flare-type membrane inflatable vehicle in suborbital reentry, Journal of Spacecraft and Rockets, Vol.54, No.5 (2017), pp.993-1004.
Yamada, K., Nagata, Y., Abe, T., Suzuki, K., Imamura, O., and Akita, D., Suborbital reentry demonstration of inflatable flare-type thin-membrane aeroshell using a sounding rocket, Journal of Spacecraft and Rockets, Vol.52, No.1 (2015), pp.275–284.