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Motion Analysis of Captive Platform System Constructed from Airship and Tether

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The existence of a platform at the stratosphere is expected to be the role to gain a foothold in space. When the platform is employed airship in, it is transported by advection due to its lighter-than-air body. Thereupon, a mooring of platform is reasonable in order to incarnate fixed-point platform. Conception of a captive platform system is similar to the Rockoon one which rendered remarkable services for the space observation of the early days. Therefore, the application of captive platform system to the launch site is highly expected in order to realize the space transportation system with a large quantity and high frequency. In this study, the motion of a captive platform system constructed from an airship and tethers is analyzed in order to ensure that the motion of a captive platform system is practically incarnated. Moreover, the sensitivities of aerodynamic performance and buoyancy of the airship is observed. Consequently, the practically incarnated motion of a captive platform system has been identified under the condition of the storm environment. Furthermore, the reduction of the advection distance driven away by the storm has been quantitatively indicated under the different conditions of aerodynamic performance and buoyancy of the airship. The sensitivities of the lift and buoyancy of the airship for the motion of a system has been revealed in order to conceptually design airship geometry.

I. Introduction

When the mooring of a platform at the stratosphere is considered, it is expected to be the role to gain a foothold in space. The conception of a stratosphere platform is known to have been studied and developed by Japan Aerospace Exploration Agency from 2003. Unfortunately, this research was a halfway development, however, its validity is never lost. It is considerable that the most essential point of a stratosphere platform is expected to become a launch site for space transportation. That is, a conception of a stratosphere platform is similar to the Rockoon system[1] which rendered remarkable services for the space observation at the early days as 50's and 60's. A captive-type stratosphere platform is efficient in order to take charge of the role of a launch site in behalf of Rockoon system.

Recently, since the advantage to launch at the stratosphere is noted for the viewpoint of space transportation with high frequency, the employment of airplanes has been tried[2,3]. Although the upper limitation of the payload weight in the existent airplanes is roughly 100 [ton], the employment of an airplane has the possibility of the primary manner for the space transportation with high frequency. The advantage of the manner using an airplane over the Rockoon system is to initially reserve the kinetic energy due to near-sonic speed at the stratosphere. However, there are several technical assignments regarding installation and separation to make the most of the above advantage. In addition, since this kinetic energy can be converted into the Rockoon altitude of 5 [km] at most, a captive platform system can cover the manner using airplane.

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Moreover, a captive platform system can be applied to multidisciplinary regions such as agriculture[4], defense[5], meteorology[6], environmental science[7], and telecommunication[8]. As the influence of the cloud can be ignored at the altitude of over 10 [km], it is especially expected to be the role as the bridge between space and the ground. The advantages of a captive platform system are that 1) the mooring of the platform can be performed with no thrust and 2) a platform does not have to deposit on the ground due to the existence of the tether. Tether can be utilized for the transfer of payload, the electricity supply, and the replenishment of floating gas because tether itself becomes pipeline and also climber can employ tether.

The goal of the conception is to ensure the captive platform system using an airship and a tether. As a first step, the geometry of airship is conceptually designed. Since the body of the airship will be membrane structure so as to be downsizing and lightening, the manner and assignment of its manufacturing are elucidated after the concrete geometry of airship is designed. As there should be the constraint that a platform is captive situation, the behavior of the system constructed between an airship and a tether under the condition of severe weather will be estimated in order to elucidate whether the system is practical. As a second step, the mission will be designed and also the instruments for the mission requirement as avionics and climber should be developed. As a captive platform system itself would like to be kept mooring at the stratosphere, transport manner using climber will be considered in order to bear payload, flaring gas, and other instruments. This step is for the concrete manufacturing phase. As a third step, the reclamation of the market and the construction of the business model will be constructed in order to usefully utilize the system. This assignment is a further step for engineering assignments. The standing point of the present study is on the above first step. In the present study, the effects due to the distinction of the aerodynamic performance of the airship will be focused. The motion of the system constructed by an airship and a tether is analyzed in advance in order to implement the conceptual design of an airship and a tether. The objective of this analysis is demonstrating the validity and possibility of a conception of the captive platform system using an airship and a tether. Moreover, the effect on the motion of the system that the distinction of aerodynamic performance on airship (it depends on the geometry of airship) exerts will be quantitatively elucidated for the sizing of the airship.

II. Candidates of airship geometry

A. Conversion from balloon into airship

When a fixed point is merely put on the stratosphere, a captive balloon is sufficient for its practicability so that the operation can be simply performed. The problems not to be able to easily employ a captive balloon are 1) whether a tether with long length and sufficient strength exists and 2) advection distance of a captive platform due to wind around the ground. The possibility of the present materials with high specific strength as the candidates of the tether can be investigated by using the general public data on the web (therefore,

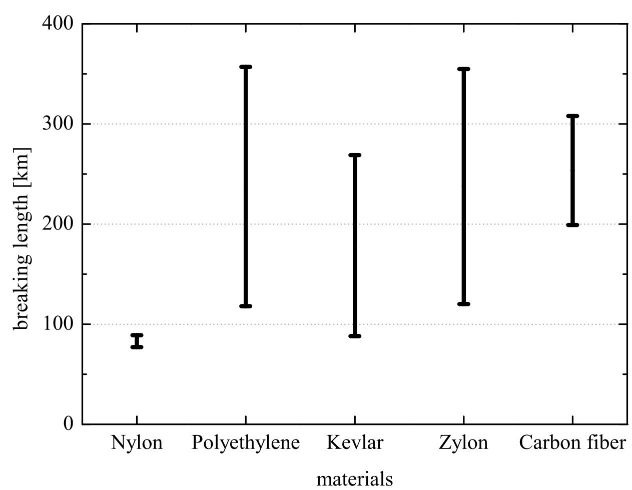

Figure 1. Comparison of breaking length among the typical materials with high performance for specific strength.

numerous references will be omitted). Figure 1 shows the data of the representative materials with high specific strength. This figure shows the breaking length in behalf of the specific strength of them, which is the value to divide specific strength for the gravitational acceleration. The breaking length is the maximum length of a vertical column of material which can suspend its own weight under the condition of support at the top of material when the cross section of material is assumed to be fixed. The values of the breaking lengths of each material have the range because of the multi-kinds of an identical material. Therefore, the minimum value of the breaking length should be aimed at. Figure 1 reveals that the present five materials have the affordability to utilize for tether at the altitude of 20 [km]. When a material is consistently selected, its weight, cost, surface roughness, and manufacturization should be considered. The strength characteristic indicates that there are practically candidates for tether.

B. Sloughing off from representative axisymmetric airship

The previous stratosphere platform had been developed by using the axisymmetric geometry like as representative airships[9–11]. Since an axisymmetric conventional airship should have thrust and also it postulates the maintenance on the ground, the operability of an airship should be foremost improved and surmounted. Thereupon, a new design concept named as hybrid airship[12, 13] was proposed at the middle of 90's. Hybrid airship is the hybridization between airplane with lift and airship with buoyancy. That is, hybrid airship can be considered as the airplane with no body weight. The airplane with no body weight can easily operate and it has outstanding aerodynamic performance for not only cruising condition but also low speed one, whereas conventional axisymmetric airship is necessary to perform complicated operations regarding loading and unloading ballast in order to control its buoyancy. In addition, hybrid airship can be a smaller volume than a conventional one. The effective thruster and appropriate control under the conditions of high altitude and low speed are required in order to operate it at the stratosphere as a platform.

C. Aerodynamic performance of airship

The characteristics of typical airships in Table 1. No.1 to 7 are axisymmetric airships, and No.8 and 9 are hybrid airships. The reference area S_{ref} shown in Table 1 is defined by the following equation.

$$S_{\mathrm{ref}} = V^{\frac{2}{3}}. \tag{1}$$

Where, V is the volume of the gasbag which floating gas is filled. All airships have the similar operational condition as follows;

$$Re \geq 10^7,\ M < 0.2. \tag{2}$$

The aspect ration AR for axisymmetric airship is defined by the following equation. FR is the aspect ratio in the case to look down body.

$$AR = \frac{4}{\pi FR}. \tag{3}$$

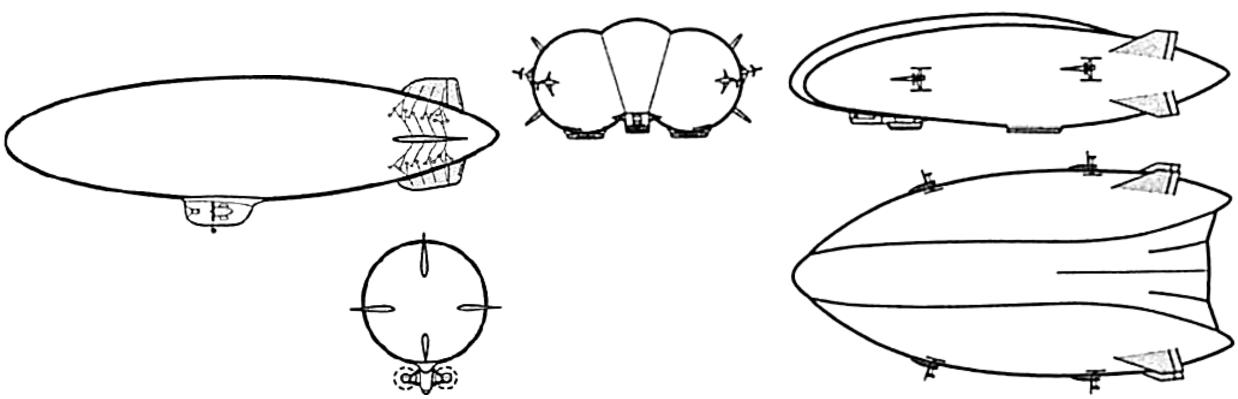

Figure 2. Typical geometries of axisymmetric[9] and hybrid[13] airships.

Table 1. Aerodynamic performances of typical airships.

No.	*Vehicle*	AR	$C_{L\alpha}$	K	C_{D0}
1[9]	BoR, FR= 7.2	0.18	0.005	3.7	0.028
2[9]	BoR, FR= 6.0	0.21	0.006	2.9	0.030
3[9]	BoR, FR= 4.8	0.27	0.0088	1.7	0.0285
4[9]	BoR, FR= 3.6	0.35	0.007	1.3	0.031
5a[10]	USS Akron w/o tails, FR= 5.9	0.22	0.0063	2.8	0.019
5b[10]	USS Akron + tails, FR= 5.9	0.23	0.0125	1.24	0.025
6a[11]	ZP5K w/o tails, FR= 4.4	0.29	0.0066	2.0	0.0152
6b[11]	ZP5K + tails, FR= 4.4	0.3	0.0115	0.9	0.026
7a[12,13]	HALE w/o tails, FR= 3.2	0.4	0.008	1.15	0.016
7b[12,13]	HALE + tails, FR= 3.2	0.41	0.0122	0.55	0.024
8[12,13]	P-791	0.54	0.046	0.32	0.096
9[12,13]	HA-1	0.60	0.045	0.28	0.033

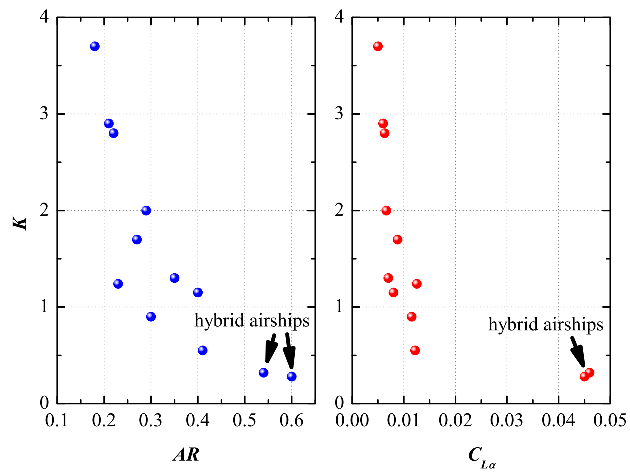

Figure 3. Comparison of the factor of induced drag, aspect ratio, and induced drag coefficient.

K denotes the factor for induced drag. It is defined by the following equation using the induced drag coefficient C_{D_L}.

$$K = \frac{C_{D_L}}{C_L^2}. \tag{4}$$

Figure 3 shows that K is gently decreased when AR becomes large. On the other hand, although K reduces linearly when C_{L_α} becomes large, K of hybrid airship is not on its extended line. Figure 3 indicates that hybrid airship surpasses axisymmetric one in aerodynamic performance.

III. Analysis model for motion of captive platform system

A. Derivation of governing equation for motion of captive platform system

First of all, the governing equation as the equation of motion to describe the motion of the captive platform system constructed by an airship and a tether will be derived. The coordinate shown in Fig. 4 is considered. An optional vector of the wind which is operated against tether $\boldsymbol{w}$ is defined on x-y plane. θ [deg] is the inclination angle of the tether on cutting plane. ϕ [deg] is the axis for wind direction on x-y plane, which is set to be counterclockwise from x axis.

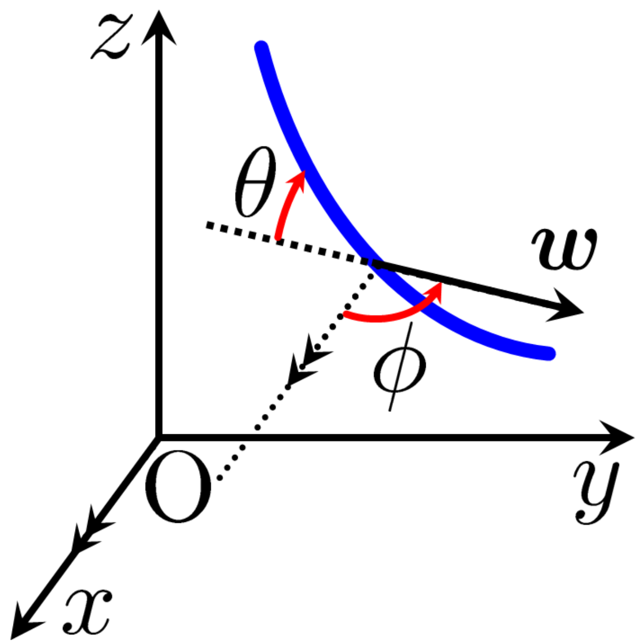

Figure 4. Coordinate for analysis of the motion of captive platform system constructed by an airship and a tether. Blue line imitates tether.

The unit tangent vector for tether $\boldsymbol{t}$ is described as the following equation.

$$\boldsymbol{t} = \frac{dx}{ds}\boldsymbol{i} + \frac{dy}{ds}\boldsymbol{j} + \frac{dz}{ds}\boldsymbol{k}. \tag{5}$$

ds denotes the infinitesimal length of tether. Where, the following equations are geometrically described.

$$\begin{aligned} dx &= ds\cos\theta\cos\phi, \\ dy &= ds\cos\theta\sin\phi, \\ dz &= ds\sin\theta. \end{aligned} \tag{6}$$

Therefore, $\boldsymbol{t}$ is described as the following equation.

$$\boldsymbol{t} = \cos\theta\cos\phi\boldsymbol{i} + \cos\theta\sin\phi\boldsymbol{j} + \sin\theta\boldsymbol{k}. \tag{7}$$

Moreover, the tension for tether T [N] and the inclination of tether θ [deg] are also geometrically described as the following respective equations.

$$\frac{dT}{ds} = D_{w_{xy}}\sin\theta\cos\theta - W\sin\theta, \tag{8}$$

$$-T\frac{d\theta}{ds} = D_{w_{xy}}\sin^2\theta + W\cos\theta, \tag{9}$$

where, $D_{w_{xy}}$ [N/km] denotes the drag of tether on x-y plane due to wind. W [N/km] is the weight of tether for unit length. The governing equation is finally derived by using eqs. (6), (8), and (9) as follows.

$$\frac{d}{dz}\begin{bmatrix} T \\ \theta \\ x \\ y \\ s \end{bmatrix} = \begin{bmatrix} D_{w_{xy}}\cos\theta - W \\ -\dfrac{D_{w_{xy}}\sin\theta + W\cot\theta}{T} \\ \cot\theta\cos\phi \\ \cot\theta\sin\phi \\ \csc\theta \end{bmatrix}. \tag{10}$$

The present $D_{w_{xy}}$ is defined as the following equation.

$$D_{w_{xy}} = C_D \cdot \frac{1}{2}\rho_{\mathrm{air}}(z)w^2(z) \cdot S_{\mathrm{ref}}. \tag{11}$$

C_D is the drag coefficient of cylinder. $\rho_{\mathrm{air}}(z)$ [kg/m^3] is the air density with altitude z. $w(z)$ [m/sec] is wind speed with altitude z. S_{ref} [m^2] denotes the reference area of tether. The cross section of the present tether is assumed as circle with 50 [mm] diameter.

The initial conditions to connect between tether and airship at upper edge of tether are considered in order to analyze eq. (10) for T and θ. When the tension at the upper edge of tether is defined as T_0 and also the inclination angle at the upper edge of tether is define as θ_0, the initial conditions can be geometrically considered as the following equations, respectively.

$$T_0 = \sqrt{(L+B)^2 + D^2}, \tag{12}$$

$$\tan\theta_0 = \frac{L+B}{D}. \tag{13}$$

L, B, and D respectively describe the lift, the buoyancy, and the drag of airship.

Here, it will be confirmed that an optional vector of wind become the unit vector when an optional vector of wind for tether on x-y plane is considered on the above governing equation. An optional vector of wind which is operated against tether $\boldsymbol{w}$ is considered on x-y plane. $\boldsymbol{w}$ is constructed by the following components.

$$\boldsymbol{w} = w\cos\phi\boldsymbol{i} + w\sin\phi\boldsymbol{j}. \tag{14}$$

The normal vector of wind is defined as $\boldsymbol{w}_\perp$ and the tangent vector of wind is also defined as $\boldsymbol{w}_\parallel$. As the wind direction is ϕ [deg], $\boldsymbol{w}_\perp$ is described as follows;

$$\begin{aligned} \boldsymbol{w}_\perp &= (\boldsymbol{t}\times\boldsymbol{w})\times\boldsymbol{t} \\ &= \boldsymbol{w} - \boldsymbol{t}(\boldsymbol{w}\cdot\boldsymbol{t}) \\ &= w\sin^2\theta\cos\phi\boldsymbol{i} + w\sin^2\theta\sin\phi\boldsymbol{j} - w\sin\theta\cos\theta\boldsymbol{k}. \end{aligned} \tag{15}$$

Now,

$$\boldsymbol{w} = \boldsymbol{w}_\perp + \boldsymbol{w}_\parallel. \tag{16}$$

Therefore, $\boldsymbol{w}_\parallel$ describes as follows;

$$\begin{aligned} \boldsymbol{w}_\parallel &= \boldsymbol{t}(\boldsymbol{w}\cdot\boldsymbol{t}) \\ &= w\cos^2\theta\cos\phi\boldsymbol{i} + w\cos^2\theta\sin\phi\boldsymbol{j} + w\sin\theta\cos\theta\boldsymbol{k}. \end{aligned} \tag{17}$$

Finally,

$$\begin{aligned} ||\boldsymbol{w}_\perp|| &= w\sin\theta, \\ ||\boldsymbol{w}_\parallel|| &= w\cos\theta. \end{aligned} \tag{18}$$

Thereupon, $\boldsymbol{w}_\perp$ is the unit normal vector, $\boldsymbol{w}_\parallel$ is the unit tangent vector, and $\boldsymbol{w}$ is the unit vector on the present governing equation.

B. Computational conditions

Computational conditions regarding tether will be summarized. C_D, which is largely estimated due to tolerance, is set to be 1.5 from the drag coefficient of the flow around a three-dimensional cylinder under $Re \sim 10^{5\sim7}$. Interpolation data based on that of the meteorological agency in Japan is employed for $w(z)$. Since the diameter of 50 [mm] for tether is assumed, S_{ref} is set to be 50 [m^2]. The weight of the tether is also assumed as 3×10^3 [kg/km].

On the other hand, the computational conditions regarding airship will be also summarized. The drag coefficient of the airship is set to be 0.06. Wind speed for airship is set to be 50 [m/sec], which is the maximum value in the present wind data. Indeed, Fig. 5 shows that the stratosphere around the altitude of 20 [km] has wind speed under 40 [m/sec], however, the present analysis is performed under tolerant condition. As it is considered that the present airship has the buoyancy of 160 [ton]. The present study

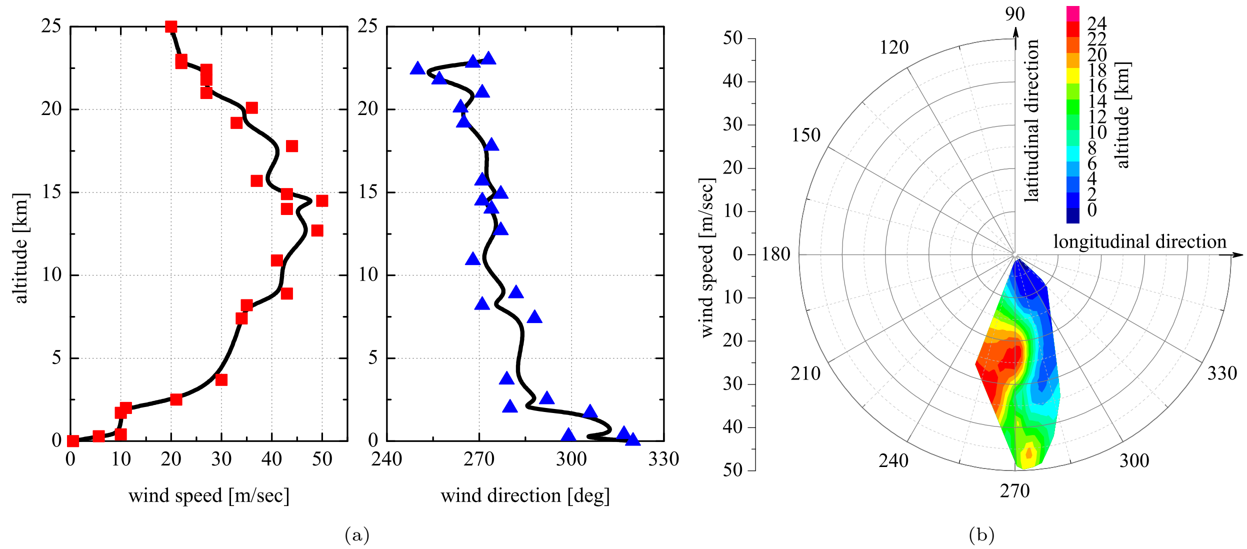

Figure 5. Wind data for the present analysis. (a) The wind data regarding speed and direction as the input for analysis under the condition of windstorm from the meteorological agency in Japan. The plots are the exact data and the black curve is proximate B-spline. (b) Visualization of the data shown in (a) on a two-dimensional plane. The length describes wind speed. As direction corresponds to that of the map, 90 [deg] shows the north direction. Color denotes altitude.

assumes to use hydrogen H_2 for floating gas of airship. H_2, which there is a large difference between H_2 and the air regarding density, is avoided employing due to easy ignition. However, it is considerable that the safety for ignition can be secured in the condition to generate the body without spark due to the idea of the manufacture manner for membrane structure. Therefore, the following equation can be considered between the buoyancy B and the volume V of airship with air density ρ_{air} and hydrogen density ρ_{H_2}.

$$B = V(\rho_{\text{air}}(z) - \rho_{\text{H}_2}(z)) \tag{19}$$

Since the reference area of the airship is defined as $V^{2/3}$, eq. (19) gives it. When B is 160 [ton], V is roughly 1.4×10^6 [m^3]. The friction drag is minimum when the ratio between the major and minor axes is set to be approximately 3.9 in the case that the shape of an airship is spheroid[14]. Thereupon, the minor axis is approximately 40 [m].

IV. Results

A. Sensitivity of lift of airship

Figure 6 shows that the behavior of the tether in two cases that the lift of the airship is zero and the lift of the airship is equal to the buoyancy of it. This figure reveals that the order of the advection distance of an airship is 10^0 [km] from a connecting point on the ground even when an airship does not develop the lift under the condition of a windstorm. Note that the essential point of this order of the advection distance depends on a small number of C_D of 0.06 on airship. Moreover, Fig. 6 also demonstrates that the lift developed by hybrid airship reduces the advection distance. The transformation of the behavior of the tether for wind corresponds to the wind speed and wind direction.

Figure 7 shows the sensitivity of lift of the airship for the behavior of the captive platform system. The difference of tension T on the tether is shown in Fig. 7(a). The difference of T seems to be linear. However, there is no linear correlation of the initial value of tension T_0 because there is no linearity between the fluctuation of lift ΔL and the fluctuation of tension ΔT described by eq. (12). In addition, eq. (10) reveals the non-linearity between L and T. As a result, tension on the tether has non-linear behavior for the lift of an airship. Moreover, the minimum value of the tension is placed on the connection between the tether and the ground. As the altitude is greater, the tension increases. The results indicate that the connection point between the tether and the airship has a higher possibility of the cutting compared with that between the tether and the ground. The assignment regarding the manner of the connection between the tether and the

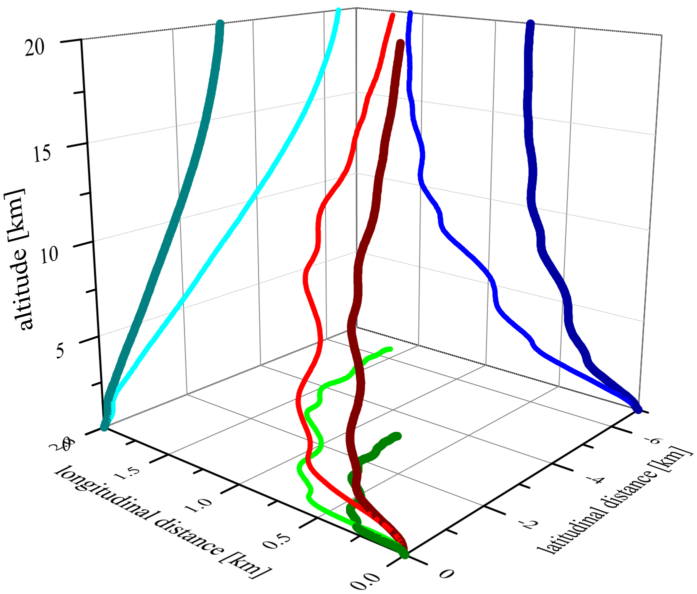

Figure 6. Computational results of behavior of tether for axisymmetric and hybrid airships. Whereas the primary color describes the result for axisymmetric airship (the lift of 0), the obscure color describes the result for hybrid airship (the lift is equal to buoyancy). Red shows the three-dimensional behavior of tether, green shows the result that the three-dimensional behavior of tether is projected onto x-y plane, blue shows the result projected onto x-z plane, and cyan shows the result projected onto y-z plane, respectively The origin is set to be a connecting point on the ground.

airship should be considered.

On the other hand, the difference of the inclination angle θ on tether can be observed in Fig. 7(b). This figure shows the non-linear behavior of θ. The behavior of θ is similar to the above that of T. There is no linear correlation of the initial value of inclination angle θ_0 because there is no linearity between the fluctuation of lift ΔL and the fluctuation of inclination angle $\Delta\theta$ described by eq. (13). In addition, eq. (10) reveals the non-linearity between L and θ. As a consequence, the inclination on tether has non-linear behavior for the lift of an airship.

Consequently, advection distance of tether becomes non-linear shown in Fig. 7(c) which projects behavior of tether onto x-y plane. Moreover, as the lift of an airship is increased more, the efficacy to restrict the advection distance of tether becomes wearing off shown in this figure. That is, since the efficacy of the restriction of the advection distance is large when the generation of lift is considered for the representative axisymmetric airship because of no lift. The concept of hybrid-type airship is essential for captive platform system regardless of the magnitude of lift.

Since the stratosphere has the wind with the speed of roughly 20 [m/sec] all the time, the body size can be small when the hybrid airship with the lift which is roughly equal to the buoyancy is considered. Moreover, the mooring region in the stratosphere can be also narrowed. It is difficult that balloon flies owing to wind, whereas kite needs wind in order to fly. The performance should be achieved in the conceptual design of the geometry of the airship to redeem each disadvantage of balloon and kite.

B. Sensitivity of buoyancy of airship

Figure 8 indicates the sensitivity of buoyancy for the behavior of the tether. The difference of tension T on the tether is shown in Fig. 8(a). As the buoyancy of an airship is reduced less, T decreases. The reference area $S_{\rm ref}$ is changed because the size of the airship body varies due to the difference in the buoyancy of the airship. Therefore, the variation of T is non-linear for the buoyancy of the airship. Since the reference area $S_{\rm ref}$ is reduced when the buoyancy of airship decreases, T in the vicinity of an airship at an altitude of 20 [km] diminishes. That is, distribution of T gradually corresponds to wind speed, as the buoyancy of the airship becomes small.

On the other hand, Fig. 8(b) reveals that tether slackens in the vicinity of the ground because of the reduction of the buoyancy of the airship. Since the buoyancy of 40 [ton] is roughly equal to the weight of

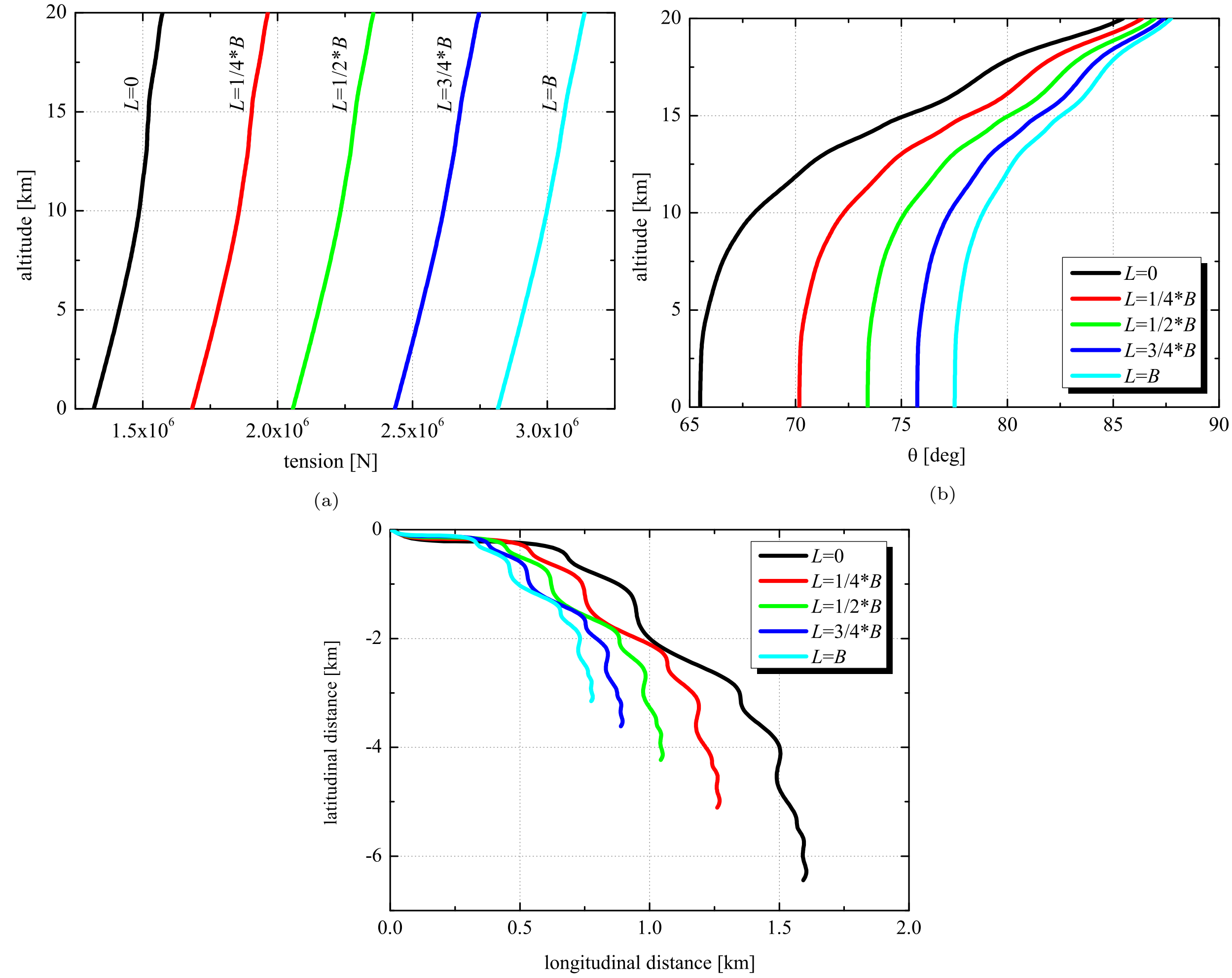

Figure 7. Influence of sensitivity of lift of airship. (a) Distribution of tension on the tether for altitude. (b) Distribution of inclination of the tether on cutting plane for altitude. (c) Comparison of the behavior of tether projected onto x-y plane.

the tether itself, tether lies on the ground when the buoyancy of the airship is less than 40 [ton] due to own weight of the tether. The lightweight-design is one of the significant assignment for captive platform system as well as existent launch systems.

The advection distance of tether shown in Fig. 8(c) which is the projected behavior of tether onto x-y plane indicates that the reduction of the buoyancy of airship effects on the rapid non-linear rise of the advection distance. It is necessary that the buoyancy balances the weights of an airship and tether themselves at least in order to obtain the practical behavior of tether. Since there is a tradeoff between the tension on the tether and the advection distance of airship, the compromise point between the maximum allowable tension and the body size should be found on the conceptual design of an airship.

V. Conclusions

Behavior of the tether for the mooring of the captive stratosphere platform using an airship has been analyzed in order to elucidate the possibility of it. The two types of geometry of the airship were regarded as representative axisymmetric-type and hybrid-type those so that the difference of the motion of captive platform system was quantitatively investigated. Consequently, it is revealed that the captive platform system constructed by an airship and tether has a possibility because an advection distance of the system under the condition of windstorm is appropriate due to its order of 10^0 [km] even when an airship has no lift.

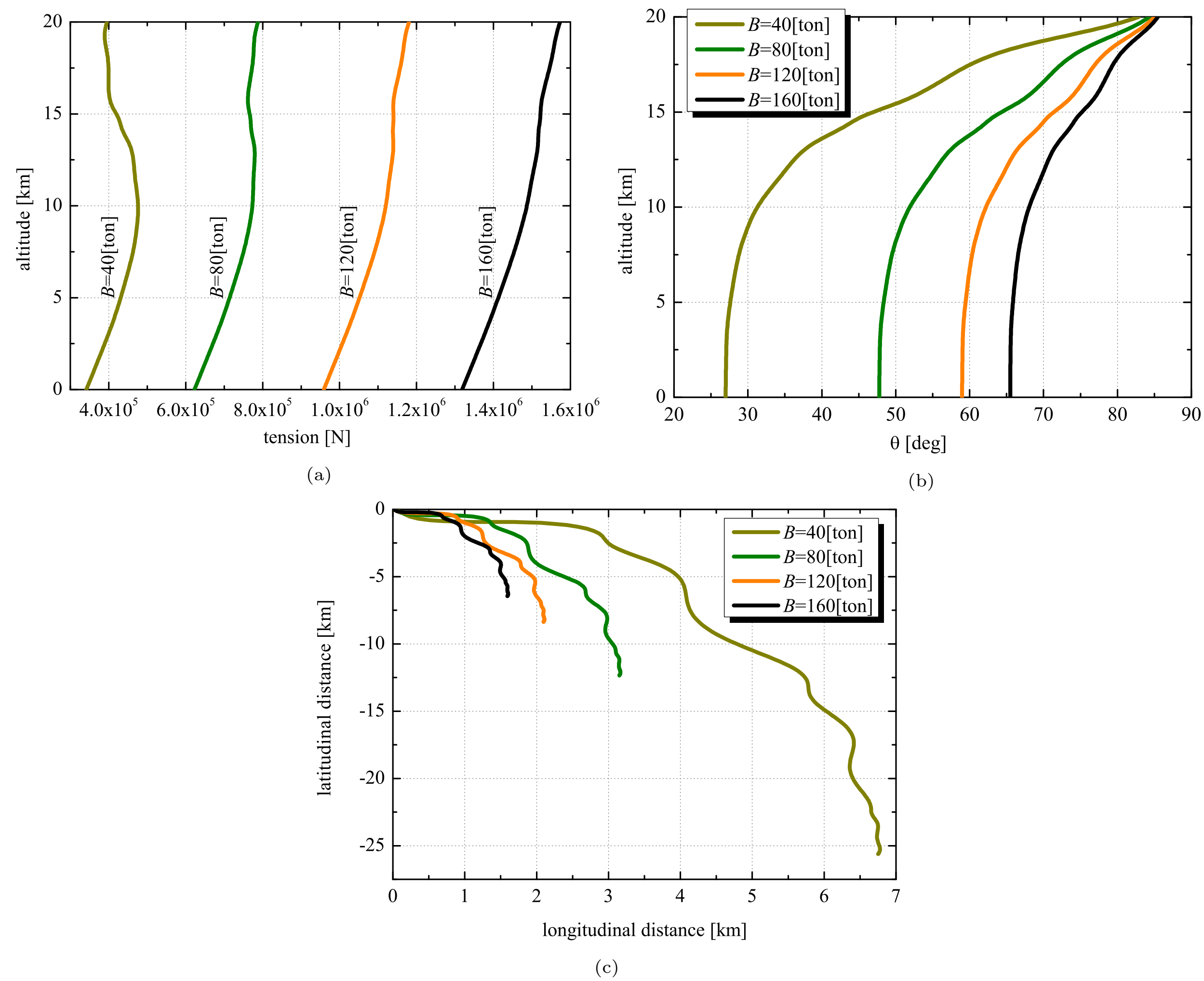

Figure 8. Influence of the sensitivity of buoyancy of airship. (a) Distribution of tension on tether for altitude. (b) Distribution of inclination of tether on cutting plane for altitude. (c) Comparison of the behavior of tether projected onto x-y plane.

Moreover, the effect of the distinction regarding the aerodynamic performance of the airship on the motion of the system has been quantitatively revealed. The tension on tether non-linearly increases and the advection distance is also non-linearly reduced when the lift of airship increases. Moreover, the tension of tether is non-linearly reduced and the advection distance non-linearly and hugely increases when the buoyancy of airship is reduced. The tradeoffs among the maximum allowable tension, the advection distance of airship, and the buoyancy of airship should be considered in order to define the scale of airship. The sizing of the airship will be conceptually designed based on the present knowledge after the definition of the concrete mission.

Acknowledgments

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