Kinetic Analysis of Vectored Electric Propulsion System for Stratosphere Airship

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Abstract: To enhance the controllability of stratosphere airship, a vectored electric propulsion system is used. By using the Lagrangian method, a kinetic model of the vectored electric propulsion system is established and validated through ground tests. The fake gyroscopic torque is first proposed, which the vector mechanism should overcome besides the inertial torque and the gravitational torque. The fake gyroscopic torque is caused by the difference between inertial moments about two principal inertial axes of the propeller in the rotating plane, appears only when the propeller is rotating and is proportional with the rotation speed. It is a sinusoidal pulse, with a frequency that is twice of the rotation speed. Considering the fake gyroscope torque pulse and aerodynamic efficiency, three blade propeller is recommended for the vectored propulsion system used for stratosphere airship.

Key words: stratosphere airship; vectored electric propulsion system; kinetic model; vector torque; fake gyroscopic torque; blade number

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0 Introduction

Stratosphere airship is defined as lighter-than-air vehicle with propulsion system operating in the stratosphere[1]. Researches on stratosphere airships are currently under project at different stages over the world[2,3]. Mass of works are undergoing to resolve some key technologies, and to demonstrate the engineering feasibility and potential utility. Subject to integrated design method, power supply and management technic, electric propulsion systems were used for those conceptual designs of stratosphere airships.

Recently, stratosphere demonstrating airships, undertaken by Korea Aerospace Research Institute (KARI) [4,5], Japan Aerospace Exploration Agency (JAXA)[5,6], U. S. Army Space and Missile Defense Command/Army Forces Strategic Command (USASMDC/ARSTRAT)[7-10], were all equipped with vectored electric propulsion systems.

On domestic researches, aimed for stratosphere airships, ZHIYUAN-1 Airship[11], made by Shanghai Jiaotong University in 2009, and the KF series airships, manufactured by the Academy of Opto-electronics, Chinese Academy of Sciences, from 2005, were all equipped with vectored electric propulsion systems.

Vectored electric propulsion system is help to enhance the controllability of an airship, to take off and land vertically, to hover automatically and track the given loop. Vectored electric propulsion system in the paper, mounted on starboard and portside, can benefit by obtaining more torques yaw though the speed deference of two propellers and minimizing the structure scale of the gondola. It contains propulsion motor, motor control module, propeller and pitch mechanism for steering the thrust. The pitch mechanism is motor driven, composed with servo motor and worm gearbox.

The objective of the paper is finding out the

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principle of such a vectored electric propulsion system is working on, and taking ground tests to validate.

1 Kinetic Modeling

The vectored electric propulsion system is simply illustrated in Fig. 1.

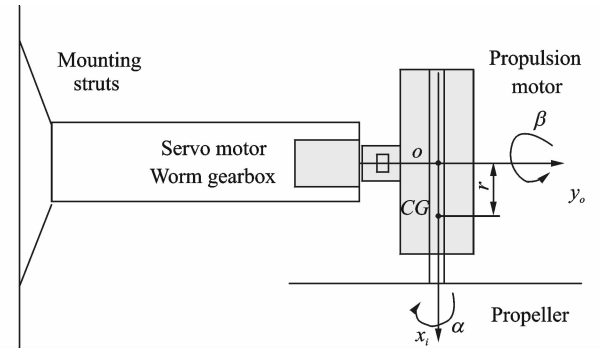

Fig. 1 Illustration of vectored electric propulsion system

Considering the system in Fig. 1, it has two degrees of freedom of motion, which are steering parts (containing the propulsion motor and the propeller) pitch about the mounting struts and the propeller rotating about its own shaft. α reprents the rotation angle of the propeller and β the rotation angle of the steering parts.

$oxyz$ is the fixed refrence frame (inertial frame) fixed on the mounting struts. $ox_oy_oz_o$ is the moving refrence frame fixed on the steering parts. $ox_iy_iz_i$ is the moving refrence frame fixed on the propeller.

Relationships between those three refrence frames are, $oxyz \rightarrow$ rotating β about y-axis $\rightarrow$ $ox_oy_oz_o \rightarrow$ rotating α about x_o-axis $\rightarrow ox_iy_iz_i$.

Notation m is the total mass of the steering parts whose center of mass is on x_i-axis with a distance of r from origin point o.

$\boldsymbol{J}_o = \mathrm{diag}(J_{xo}, J_{yo}, J_{zo})$ is the matrix of inertia moment of the propulsion motor, with respect to three axis of reference frame $ox_oy_oz_o$.

$\boldsymbol{J}_i = \mathrm{diag}(J_{xi}, J_{yi}, J_{zi})$ is the matrix of inertia moment of the propeller, with respect to three axis of reference frame $ox_iy_iz_i$.

$\boldsymbol{\omega}^i, \boldsymbol{\omega}^o$ are the vector of the angular speed (absolute angular speed) of the propeller and steering parts rotating about the fixed coordinates.

$$\boldsymbol{\omega}^i = \dot{\boldsymbol{\alpha}} + \dot{\boldsymbol{\beta}} \tag{1}$$

$$\boldsymbol{\omega}^o = \dot{\boldsymbol{\beta}} \tag{2}$$

where $\dot{\boldsymbol{\alpha}}$ is the vector of propeller position on axis $ox_oy_oz_o$ and $\dot{\boldsymbol{\beta}}$ the vector of steering parts position on axis $oxyz$. Considering the transformation of each axis, $\dot{\boldsymbol{\alpha}}$, $\dot{\boldsymbol{\beta}}$ are easily written as a function of α, β, which is omitted here. Taking α, β as the generalized coordinates, the total kinetic of the vectored electric propulsion system can be written as

$$T = T_i + T_o = \frac{1}{2}[\boldsymbol{\omega}_i^i]^{\mathrm{T}} \boldsymbol{J}_i \boldsymbol{\omega}_i^i + \frac{1}{2} J_{yo} \dot{\beta}^2 \tag{3}$$

where $\boldsymbol{\omega}_i^i$ is $\boldsymbol{\omega}^i$ described on axis $ox_iy_iz_i$, thus

$$T_i = \frac{1}{2}[\boldsymbol{\omega}_i^i]^{\mathrm{T}} \boldsymbol{J}_i \boldsymbol{\omega}_i^i =$$

$$\frac{1}{2}[J_{xi}\dot{\alpha}^2 + J_{yi}\dot{\beta}^2\cos^2\alpha + J_{zi}\dot{\beta}^2\sin^2\alpha] \tag{4}$$

Positive forces of the system consist of the gravity, the thrust, the torque caused by the reactive force of the propeller and the torque supplied by the servo gearbox to the steering parts. The gravity is potential force. Taking the horizontal face through o as the datum face, the gravitational potential energy can be written as

$$V = -mgz = mgr\sin\beta \tag{5}$$

The concern of the paper is not the motion of the propeller but the motion of steering parts. Concerning only the generalized coordinate β, using the Lagrangian method[12], a Lagrange equation of the system can be written as

$$\frac{\mathrm{d}}{\mathrm{d}t}\left[\frac{\partial T}{\partial \dot{\beta}}\right] - \frac{\partial T}{\partial \beta} + \frac{\partial V}{\partial \beta} = M_\beta \tag{6}$$

where M_β is the generalized force with respect to the generalized coordinate β.

Since the thrust pass through the origin point o, the virtual work conducted by the virtual displacement $\delta\beta$ is zero. The torque caused by the reactive force of the propeller is vertical with the virtual displacement $\delta\beta$, so that the virtual work is zero, too. Therefore, the virtual work on the system is only conducted by the torque M_g supplied by the worm gearbox.

$$\delta W = M_g \cdot \delta\beta \tag{7}$$

Therefore, M_g is the generalized force M_β with respect to the generalized coordinate β, that is $M_g =$

M_β. Substitute $\frac{\partial T}{\partial \dot{\beta}}, \frac{\mathrm{d}}{\mathrm{d}t}\left[\frac{\partial T}{\partial \dot{\beta}}\right], \frac{\partial T}{\partial \beta}, \frac{\partial V}{\partial \beta}$ into Eq. (6)

$$(J_{yo} + J_{yi}\cos^2\alpha + J_{zi}\sin^2\alpha)\ddot{\beta} + \dot{\alpha}\dot{\beta}(J_{zi} - J_{yi})\sin 2\alpha + mgr\cos\beta = M_\beta = M_g \quad (8)$$

Eq. (8) is the general equation of kinetics for the vectored electric propulsion system.

2 Analysis of Operating Mode

The vector mechanism is operated in two modes-pitching before the propeller rotate, or pitching while the propeller is rotating. In Operating Mode I, the vector mechanism begins to pitch when the propeller is static, and after arriving at the target angular position the propeller begins to rotate. In Operating Mode II, the vector mechanism pitches while the propeller is rotating with a constant speed.

2.1 Operating Mode I

When the propeller is static, $\alpha = \alpha_0$ and $\dot{\alpha} = 0$. Substituted into the general Eq. (8), following equation can be obtained

$$M_g = (J_{yo} + J_{yi}\cos^2\alpha_0 + J_{zi}\sin^2\alpha_0)\ddot{\beta} + mgr\cos\beta \quad (9)$$

From Eq. (9), it shows that, in the mode, torques the servo motor needs to supply are the inertial torque and the gravitational torque. The inertial torque is related with the equivalent moment of inertia and the angular acceleration of steering parts. As shown in Eq. (9), the equivalent moment of inertia of steering parts is defined as

$$I_y(\alpha_0) = (J_{yo} + J_{yi}\cos^2\alpha_0 + J_{zi}\sin^2\alpha_0) \quad (10)$$

Eq. (10) shows that the equivalent moment of inertia is correlated with the initial position α_0 and the two moments of inertia about two axes of inertia of the propeller.

By seeking extreme of Eq. (10) with the extreme condition is given as

$$\sin(2\alpha_0) = 0 \quad (11)$$

Following results can be obtained.

(1) The equivalent moment of inertia is the minimum when $\alpha_0 = 0°$ and $\alpha_0 = 180°$. Therefore, torque needed from the servo motor is synchronously the minimum.

(2) The equivalent moment of inertia is the maximum when $\alpha_0 = 90°$ and $\alpha_0 = 270°$. Similarly, torque needed to supply is synchronously the maximum.

2.2 Operating Mode II

Given the angular velocity of the propeller $\dot{\alpha} = \Omega = \text{const}$, according to the general Eq. (8), M_g can be calculated as

$$M_g = (J_{yo} + J_{yi}\cos^2\alpha + J_{zi}\sin^2\alpha)\ddot{\beta} + \dot{\beta}(J_{zi} - J_{yi})\Omega\sin 2\alpha + mgr\cos\beta \quad (12)$$

where

$$\alpha = \alpha_0 + \Omega t \quad (13)$$

Compared Eq. (12) with Eq. (9), it can be found that, the servo motor need overcome a special torque caused by the rotation of the propeller, besides the inertial torque and the gravitational torque. This special torque, denoted as M_F, is called fake gyroscopic torque in the paper to differ from gyroscopic torque.

M_F is given as

$$M_F = \dot{\beta}(J_{zi} - J_{yi})\Omega\sin 2\alpha \quad (14)$$

The fake gyroscopic torque appears only when the propeller is rotating, and is proportional with the rotation speed of the propeller, which is similar with the gyroscopic torque. It is caused by $(J_{zi} - J_{yi})\Omega$, the difference between moments of inertia about two axes of inertia in the rotating plane, which is different from the gyroscopic torque that caused by $J_{xi}\Omega$, the momentum of the propeller rotating about its shaft. As consisting of a part of $\sin 2\alpha$, the fake gyroscopic torque is sinusoidal, which is the second difference from the gyroscopic torque. It is the maximum when the degree between the propeller shaft and the pitch mechanism shaft is 45° and is the minimum when the two shafts are parallel or vertical.

The inertial torque can be rewritten as

$$\ddot{\beta}I_y(\alpha) = \ddot{\beta}\left[J_{yo} + \frac{1}{2}(J_{yi} + J_{zi}) - \frac{1}{2}(J_{zi} - J_{yi})\cos 2\alpha\right] \quad (15)$$

As shown in Eq. (15), the inertial torque is also sinusoidal pulse, with a frequency that is twice of the rotation speed of the propeller.

In conclusion, in order to calculate the maximum torque that the servo motor and the gearbox need to supply, the maximum positions, maximum rotation speed of the propeller, the maximum angular velocity and angular acceleration of spinning should be taken into account. The maximum torque can be calculated by

$$M_g \approx |(J_{yo}+J_{zi})\ddot{\beta}_{\max}| + |\dot{\beta}_{\max}\Omega_{\max}(J_{zi}-J_{yi})| + |mgr| \tag{16}$$

where $\Omega_{\max}$ is the maximum rotation speed of the propeller, $\ddot{\beta}_{\max}$ the maximum angular acceleration, and $\dot{\beta}_{\max}$ the maximum angular velocity of the steering parts.

It shows in Eq. (16) that, when the gravitational torque is balanced, i. e., the center of mass is on the pitch shaft $r=0$, the maximum torque of the servo motor need to supply is in proportion with inertial moment (related with the square of the diameter) and the rotation speed of the propeller.

2.3 Discussion on blade number

As shown in Section 2.1, the sinusoidal pulse of the inertial and the fake gyroscopic torque is caused by the difference between inertial moments about two principal axes of inertia in the rotating plane.

Given a two-blade propeller, illustrated in Fig. 2. Reference frame $y_b o_b z_b$ is fixed on the propeller, in which y_b and z_b are the two principal axes of inertial in the rotating plane, parallel with y_i and z_i.

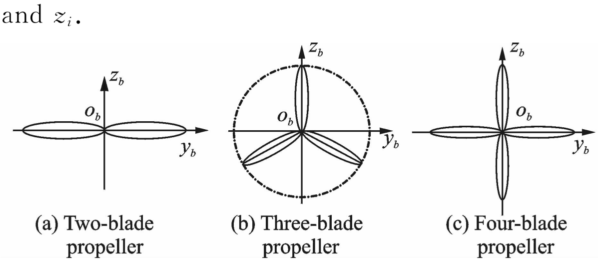

Fig. 2 Illustration of two-, three- or four-blade propeller

For a two-blade propeller (Fig. 2(a)), to simplify the calculation, it can be reduced to a flat plate with I_{yb} and I_{zb} as the inertial moment about y_b and z_b.

$$I_{yb}=\frac{1}{12}m_{\mathrm{p}}(h^2+w^2),\ I_{zb}=\frac{1}{12}m_{\mathrm{p}}(d^2+h^2) \tag{17}$$

where d is the diameter, h the thickness, w the width, and m_{p} the mass of the propeller.

Given s the distance from the center of the propeller to the origin point o, according to Parallel-Axis Theorem[13], J_{zi} and J_{yi} are given by

$$J_{zi}=m_{\mathrm{p}}s^2+I_{zb}=m_{\mathrm{p}}s^2+\frac{1}{12}m_{\mathrm{p}}(d^2+h^2) \tag{18}$$

$$J_{yi}=m_{\mathrm{p}}s^2+I_{yb}=m_{\mathrm{p}}s^2+\frac{1}{12}m_{\mathrm{p}}(h^2+w^2) \tag{19}$$

Limited to the structural and aerodynamic design method and technic, the diameter d is usually an order of magnitude lager than width w. Therefore, J_{zi} is usually much larger than J_{yi}.

The difference, $(J_{zi}-J_{yi})\Omega$, will be huge for two-blade propeller, especially when the diameter is large. The pulse may induce a sympathetic vibration to the mounting struts and the bindiny mechanism, which will result in invalidation of the vector propulsion system.

To eliminate the sinusoidal pulse, four-blade propeller, as shown in Fig. 2(c), is a good choice. For four-blade propeller, when blades are exactly uniform during manufacture, principal inertial moments about the two principal axes in the rotation plane are the same, namely $J_{zi}=J_{yi}$. Therefore, the general equation can be rewritten as

$$M_g=(J_{yo}+J_{zi})\ddot{\beta}+mgr\cos\beta \tag{20}$$

Compared with Eq. (8), it can be found that the sinusoidal pulse of the inertial and the fake gyroscopic torque disappears.

In engineering practice, four-blade propeller is disadvantageous in lower efficiency of aerodynamic and more complicated to manufacture than two- or three-blade propeller.

Three-blade propeller, Fig. 4(b), similar to four-blade propeller, has the same principal moments about the two principal axes in the rotation plane. This can be simply proved as follows.

Simplify each blade to a thin pole, given R the radius and m_{b} the mass of single blade. Then

$$I_{yb}=\frac{1}{3}m_bR^2+\frac{1}{12}m_bR^2+\frac{1}{12}m_bR^2=\frac{1}{2}m_bR^2 \tag{21}$$

$$I_{zb}=0+\frac{1}{4}m_bR^2+\frac{1}{4}m_bR^2=\frac{1}{2}m_bR^2=I_{yb} \tag{22}$$

Therfore, $J_{zi}=J_{yi}$.

Therefore, considering factors like oscillation, efficiency and manufacture, three blades are recommended for the vectored propulsion system.

3 Validation of Kinetic Model

To validate the kinetic model, ground tests are also conducted under two situations, when the propeller is static and is rotating at an angular velocity. Subjects of the test are vectored electric propulsion systems used on the KF** Airship, which are mounted on the ship centerline on starboard and portside, as shown in Fig. 3. To simplify the calculation, the propulsion motor is reduced to a homogeneous cuboid and the propeller to a plate, as in Fig. 4.

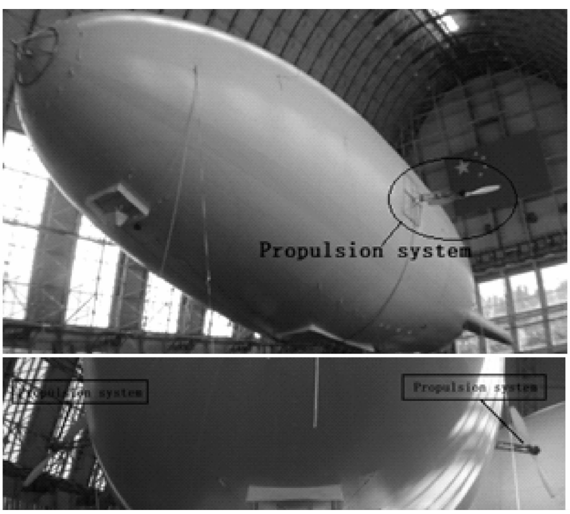

Fig. 3 Propulsion systems on KF** Airship

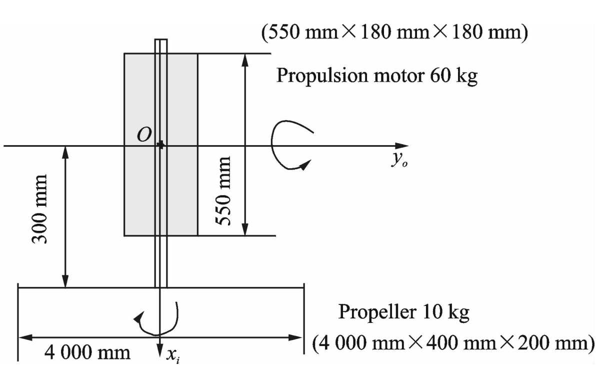

Fig. 4 Illustration of steering parts for KF** Airship

Parameters of the propeller for KF** Airship are given as follows

$m_p \approx 10$ kg, $d \approx 4$ m, $w \approx 0.4$ m, $h \approx 0.2$ m, $s \approx 0.3$ m

Then

$$J_{yi} \approx 1.1\ \text{kg}\cdot\text{m}^2,\ J_{zi} \approx 14.4\ \text{kg}\cdot\text{m}^2$$

Obviously, J_{zi} is an order of magnitude larger than J_{yi}.

Inertia moment of propulsion motor and the propeller are written as

$$\boldsymbol{J}_o = \text{diag}(J_{xo}, J_{yo}, J_{zo}) \approx \text{diag}(0.3, 1.5, 1.5) \tag{23}$$

$$\boldsymbol{J}_i = \text{diag}(J_{xi}, J_{yi}, J_{zi}) \approx \text{diag}(14.3, 1.1, 14.4) \tag{24}$$

From Eqs. (23) and (24), it can be found that inertia moment of the propeller is quite bigger than that of the propulsion motor. The inertial moment of the propeller makes up a high proportion of the equivalent inertial moment of the steering parts.

Given the angular velocity $\dot{\beta}_{\max} = 20\ °/\text{s}$, angular acceleration $\ddot{\beta}_{\max} = 20\ °/\text{s}^2$ and the distance from the center of mass of the steering parts to the origin point, $r = 0.01$ m.

When the propeller is static with an initial position of $\alpha_0 = 0°$ or $\alpha_0 = 180°$, where the propeller is parallel with the pitch mechanism shaft, the maximum torque reduces as

$$M_g = (J_{yo} + J_{yi})\ddot{\beta} + mgr \tag{25}$$

When the initial position is $\alpha_0 = 90°$ or $\alpha_0 = 270°$, where the propeller is vertical with the pitch mechanism shaft, the maximum torque reduces as

$$M_g = (J_{yo} + J_{zi})\ddot{\beta} + mgr \tag{26}$$

Substitute J_{yo}, J_{zi}, J_{yi}, m, r, α_0, and β parameters into Eqs. (25) and (26), and following results are obtained.

(1) The maximum inertia moment is 5.6 N·m and the minimum 0.9 N·m.

(2) The maximum gravitational torque is 6.9 N·m and the minimum 0 N·m.

(3) The total maximum torque is 12.5 N·m.

From above results, it can be found that equivalent inertial moments are quite different when $\alpha_0 = 0°$ and $\alpha_0 = 90°$. Those are proved with performances observed in the ground test. When the propeller is static, given the same angular acceleration and angular velocity, it is easy to turn when $\alpha_0 = 0°$ (See Fig. 5(a)) and difficult (In test results, under the same voltage, current supplied to the servo motor is larger than that of the former) when $\alpha_0 = 90°$ (See Fig. 5(b)).

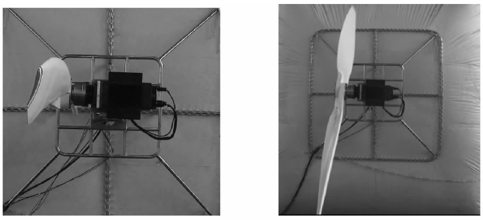
(a) α_0=0° (b) α_0=90°

Fig. 5 Propulsion system in ground test

Given the rotation speed of the propeller $\Omega_{max} = 500$ r/min. Then, according to Eq. (8),

(1) The maximum inertia torque is 5.6 N • m and the minimum 0.9 N • m.

(2) The maximum fake gyroscopic torque is 242.8 N • m and the minimum 0 N • m.

(3) The maximum gravitational torque is 9.6 N • m and the minimum 0 N • m.

(4) The total maximum torque is 258.0 N • m.

Above results show that, the fake gyroscopic torque, appearing only when the propeller is rotating, is evident as the diameter is big. It is 43 times larger than the inertia torque and 25 times larger than the gravitational torque. This also accords with ground tests. When the torque supplied is about 161 N • m, 10 times larger than the total maximum torque when the propeller is static but much smaller than the total maximum torque when the propeller is rotating, the vector mechanism will not pitch under the given angular velocity and angular acceleration, with an error of overcurrent protection of the servo motor. When the torque supplied is 315 N • m, 1.2 times larger than the total maximum torque when the propeller is rotating, the vector mechanism pitches smoothly under the given angular velocity and angular acceleration.

4 Conclusions

From above analysis, following conclusions can be obtained.

(1) When pitches before the propeller rotate, the vector mechanism should overcome inertial torque and gravitational torque. The equivalent moment of inertia, related with the initial position of the propeller, is the minimum when the propeller is parallel with the mechanism shaft and is the maximum when vertical.

(2) When pitches while the propeller is rotating, the vector mechanism should also overcome the fake gyroscopic torque, besides inertial torque and gravitational torque.

(3) The fake gyroscopic torque is caused by the difference between inertial moments about the two principal axes of inertia of the propeller in the rotating plane. It appears only when the propeller is rotating, and it is proportional with the rotation speed. It is a sinusoidal pulse with a frequency that is twice of the rotation speed, the minimum when the propeller parallel or vertical with the pitch mechanism shaft and the maximum when the degree between the two is 45°.

To pursuit the highest efficiency, propeller used for stratosphere airship is usually very large in diameter. This will result in a notable fake gyroscopic torque pulse when there are two blades. Therefore, special attention needs paid to the fake gyroscopic torque during the design of the vectored propulsion system. Since the efficiency will decline as the blade number increase, three-blade propeller is recommended for the vectored propulsion system used for stratosphere airship.

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