On C.P.-C.M. Offset Torque Generation for Tether-controlled Spinning Solar Sail

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Abstract

Today, solar sail is watched for interplanetary cruising due to its propellantless thrust system. For the solar sail technology, attitude control is one of the most important issues. The authors have proposed C.P. (centre of pressure) – C.M. (centre of mass) offset torque generation method for attitude maneuver of tether-controlled spinning solar sail. The authors conducted numerical simulations to study dynamic behaviour of the sailcraft. From the numerical simulations, tether controllability during the C.P.-C.M. offset generation is figured out. Also, the authors have estimated that the C.P.-C.M. offset method can generate enough torque compared to other methods for space exploration missions.

テザー制御スピンソーラーセイルにおける C.P.-C.M.オフセットトルク生成法に関する研究

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概要

今日ソーラーセイルは，推進剤不要な推進システムという特徴により，惑星間航行手段として注目されている．姿勢制御は，ソーラーセイルにおいて最も重要な課題の一つである．著者らは，テザー制御スピンソーラーセイルにおける姿勢制御のための C.P.（光圧中心）－C.M.（質量中心）オフセットトルク生成法を提案し，その際のソーラーセイルの動的挙動についての知見を得るために数値シミュレーションを実施した．この数値シミュレーションにより，C.P.-C.M.オフセット生成時のテザーの制御性を明らかにした．また，惑星間航行時に，C.P.-C.M.オフセット手法が他の手法と比較して十分なトルクを生成できることを見積もった．

1. Introduction

Solar sail is one of challenging technologies for interplanetary cruising and has been investigated by many researchers in the world. It is attractive because of its unique thrust system which uses solar pressure, not propellants. Thus, solar sail is effective for missions that have long duration such as deep space exploration.

In Japan, several types of spinning solar sail are investigated, and the Laboratory for Space Systems (LSS) have proposed a tether-controlled spinning solar sail is a type of tethered formation flight. In one style of the system, three satellites are located on vertices of a large thin triangular membrane, as shown in Fig. 1.

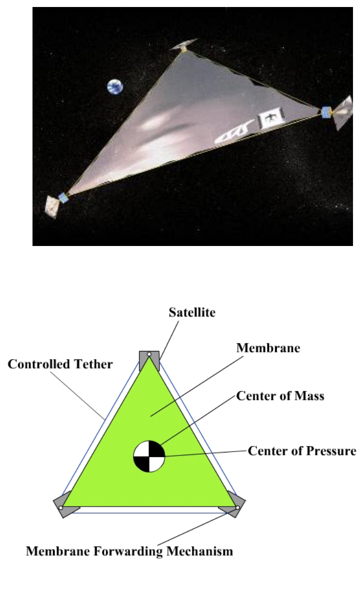


Figure 1 Tether-Controlled Spinning Solar Sail

The system spins up and the centrifugal forces are applied on the satellites by their mass. The satellites and the vertices of the membrane are connected with tethers to control relative distances between them. The proposed type of the solar sail has the following characteristics:

1) Structural Stability: Maintained during membrane deployment using controlled tethers
2) Membrane tension can be supported and controlled using boundary tethers
3) Spinning stability depends on dynamics of membrane and tether control

The authors have studied the membrane dynamics during its deployment using tether length control and membrane forwarding mechanisms by numerical simulations as well as by hardware experiments[1-6], and its usefulness and feasibility are shown.

In addition to membrane deployment, attitude control is also an important issue for solar sail technology. The authors propose C.P.-C.M. offset torque generation method for attitude maneuver, where C.P. means the centre of pressure due to solar radiation and C.M. means the centre of mass in the system. The offset between C.P. and C.M. can be generated by controlling its tether length as shown in Fig. 2, and the offset induced torque is generated for attitude maneuver. This torque generation method is one of unique methods used for tethered spinning solar sail, so that in this paper this method is considered.

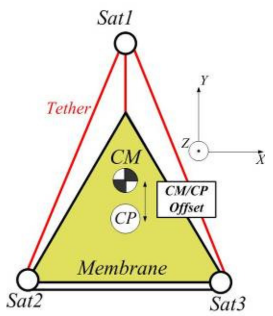


Figure 2 C.P.-C.M. Offset Generation

The paper deals with numerical simulations for dynamics of the membrane and the sub-satellites during the tether length change. In the numerical simulations, analytical model of multiple mass-spring-damper is applied to the membrane, the sub-satellites and the tethers. The dynamical behaviour and C.P.-C.M. offset are observed in the simulations using a 70m-scale solar sail model. Also, estimation of attitude angle control rate and attitude maneuver simulations are conducted and the results are shown.

2. C.P.-C.M. Offset Torque Generation

2.1 Attitude Control Methods

The following control methods can be used for the attitude maneuver of spinning solar sail:

1) Thruster

Thruster can generate large torque, but propellant is needed, and frequent use of thruster loses the solar sail's major advantage. Thus, thruster should be an assistant actuator for long duration mission such as deep space exploration.

2) Solar Pressure

This type is very small torque generator, but no propellant is necessary. Solar pressure type actuator can be classified as follows:

a) Direction-changeable petals on the sub-satellites
b) Light reflectivity-changeable device, for example, liquid crystal material on membrane
c) C.P.-C.M. offset torque generated with changing ballast position or tether length etc.

Type a) and b) are promising method for attitude control. On the other hand, type c) is one of unique methods for the tether-controlled spinning solar sail which have proposed by the authors, so that this paper focuses on type c), and the possibility of this torque generation method is investigated.

2.2 C.P.-C.M. Offset Generation for Tether-Controlled Spinning Solar Sail

Tether-controlled spinning solar sail, as shown in Fig. 1, is able to change its formation with tether length control. Relative position of a sub-satellite to membrane can be changed by changing the length of tethers between other sub-satellites and membrane, shown in Fig. 2. Tether length change makers an offset between the C.P. and C.M., and the in-plane offset torque will be generated due to its displacement. This C.P.-C.M. offset torque is used for attitude maneuver in this paper. Note that C.P. of the system is nearly equal to C.P. of the membrane.

3. Numerical Simulation

The authors conducted numerical simulations to know dynamic behaviour of the sailcraft during attitude maneuver with controlling its tether length. In this section, an analytical model and simulation results are shown.

3.1 Analytical Model

For an analytical model, a typical configuration of tether-controlled spinning solar sail is applied [7], and the assumptions are as follows:

1) Sub-Satellites

In this paper, sub-satellite's attitude is neglected for simplicity. Thus, it is approximated as point mass (nominal 10kg).

2) Membrane

Modelled as multiple mass points and connect them with spring and damper. In this paper, for simplicity, four mass points are placed on vertices and centre of the triangular membrane.

Membrane is made of Al-evaporated polyimide which light reflectivity is 0.85, and Yang's module is $E_m = 30$[GPa]. The thickness is 0.75 [μm], and its mass area density is $\rho_t = 1.0\times10^{-2}\,[\mathrm{kg/m^2}]$. The shape of membrane is regular triangle of 70 [m], so that the total mass is approximately 20 [kg].

3) Tether

Massless spring which generates only pulling force. Yang's module is $E_t = 123$[GPa],sectional area is $A_t = 1.0\times10^{-4}\,[\mathrm{m^2}]$ and mass line density is $\rho_t = 9.7\times10^{-3}\,[\mathrm{kg/m}]$ so that the mass of tether is negligible.

Tension force acts on tether is modeled as follows:

If $L_{ij} \geq L_{ij\_d}$,

$$\mathbf{T}_{ij} = k_{ij}\left(L_{ij} - L_{ij\_d}\right)\frac{\left(\mathbf{r}_j - \mathbf{r}_i\right)}{L_{ij}} \qquad (1)$$

If else,

$$\mathbf{T}_{ij} = 0 \qquad (2)$$

where

L_{ij} : relative distance between i th and j th mass point $\left(L_{ij} = \left|\mathbf{r}_j - \mathbf{r}_i\right|\right)$

L_{ij_d} : commanded length between $i-j$

$\mathbf{T}_{ij}$: tension force acts on i th mass point by $i-j$ tether

k_{ij} : spring constant of $i-j$ tether

$\mathbf{r}_i$: position vector to i th mass point from the origin

The analytical model is shown in Fig. 3.

Element numbers of the mass points are defined as shown in Fig.4:

1-3 : Sub-satellites

4-7 : Membrane (4-6 are on vertices, 7 is on center)

All sub-satellites are connected each other with tether, for example, 1st and 2nd mass point. Also, sub-satellite and the closest vertex of the membrane are connected with tether, for example, 1st and 4th mass point.

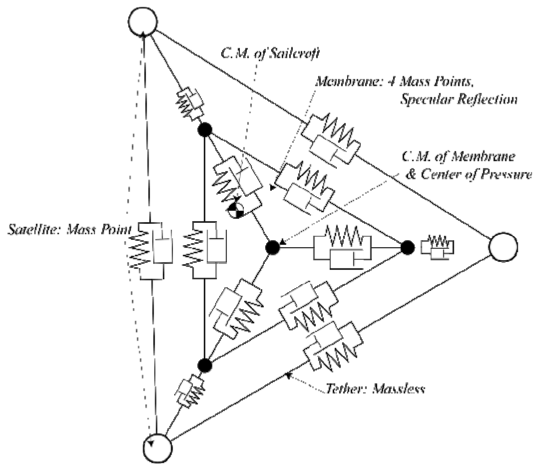


Figure 3 Numerical Simulation Model (Mass-Spring-Damper)

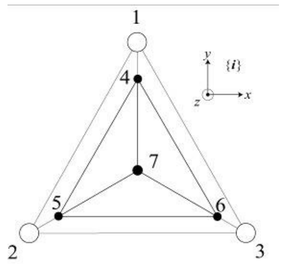


Figure 4 Mass Point Number Allocation

3.2 Tether Length Control Method

In this paper, simple method of tether length change under no solar pressure. One of sub-satellites controls tether length sinusoidally, which can be described as follows:

$$l_t = l_{sat} + \Delta l \qquad (3)$$

where

l_t : tether length between the sub-satellites

l_{sat} : nominal distance between the sub-satellites

Δl : sinusoidal tether length variation $\left(\Delta l = A_t \sin \omega_t t\right)$

Definitions of parameters are shown in Fig. 5. An example of tether length change is shown in Fig. 6. The sailcraft rotates at an initial angular velocity $\omega_{s/c}$.

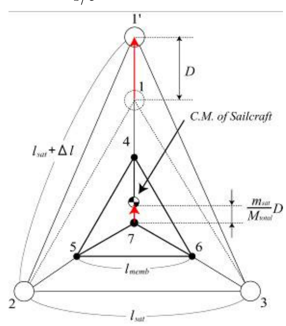


Figure 5 Tether Length Variation

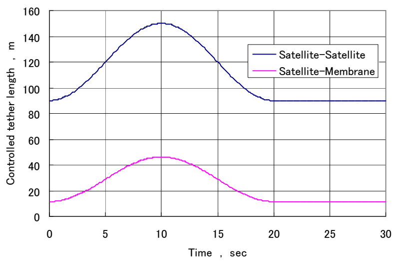
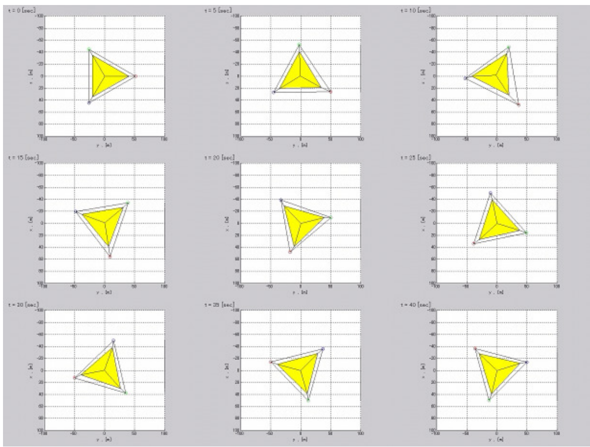


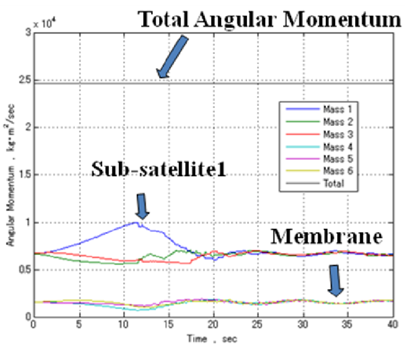
Figure 6 History of Tether Length
($A_t = 30$ [m] $T_t = 2\pi/\omega_t = 20$ [s])

3.3 Simulation Result

One successful example of numerical simulations is shown in Fig. 7, where one sub-satellites controls length of three tethers it has, to make position offset between the C.P. and C.M. Fig. 7(a) shows shape variation of the sailcraft in 3-D model, and Fig. 7(b) shows history of angular momentum during the simulation. From the figure, conservation of total angular momentum is confirmed, while angular momentum exchange between membrane and sub-satellites occurs. Although tether length change is finished, residual vibration is remained between them.



(a) 3-D View from Top



(b) History of Angular Momentum
Figure 7 One of Numerical Simulation Result
($T_t = 20$[sec], $\omega_{s/c} = 0.1$[rad/sec], $l_{sat} = 90$[m], $A_t = 5$[m])

The exchange of angular momentum during tether length change is cause of this residual vibration, as shown in Fig. 8.

When this swing gets large, membrane breaks bounds of tethers, as shown in Fig. 9. This configuration is unacceptable because it may cause a tangle of membrane and tether.

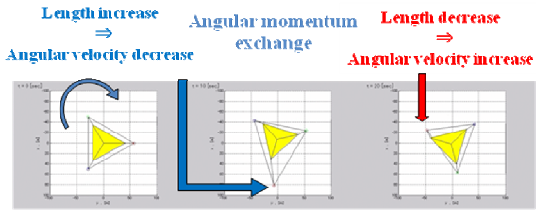


Figure 8 Excitation Vibration
($T_t = 20$[sec], $\omega_{s/c} = 0.2$[rad/sec], $l_{sat} = 100$[m], $A_t = 15$[m])

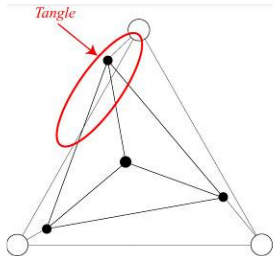


Figure 9 Unacceptable Configuration

The vibration behavior dependency on the following parameters is investigated:

l_{sat} : initial tether length between sub-satellites

m_{sat} : mass of sub-satellites

$\omega_{s/c}$: initial angular velocity of the sailcraft

ω_t : tether length change rate

Maximum tether length amplitude $A_{\max}$ which dosen't induce the unacceptable configuration during sinusoidal tether length change is obtained by changing initial angular velocity of the sailcraft and tether length change rate.

Fig. 10 and Fig. 11 show the summary of numerical simulation result. In the analysis, the following values of parameters are used:

$m_{sat} = 5, 10, 20, 40$[kg]

$l_{sat} = 100, 90, 80$ [m]

$T_t = 40, 20, 10, 5$ [sec]

$\omega_{s/c} = 0.05, 0.10, 0.20, 0.25, 0.40, 0.50, 1.00$ [rad/sec]

Fig. 10 shows linear dependency of maximum tether length amplitude $A_{\max}$ on angular velocity rate $\omega_{s/c}/\omega_t$ with changing tether length between the sub-satellites l_{sat} . Fig. 11 shows the same relationship with changing sub-satellite mass m_{sat}. It is found that the tether length controllability gets larger when the initial tether length and sub-satellite mass are large.

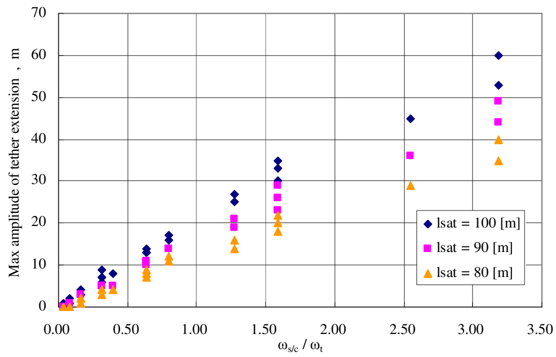


Figure 10 Dependency of $A_{\max}$ on $\omega_{s/c}/\omega_t$

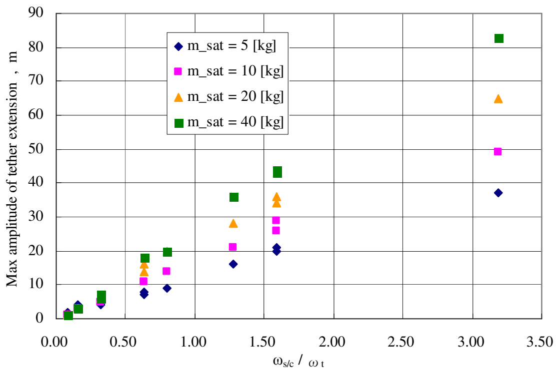


Figure 11 Dependency of $A_{\max}$ on $\omega_{s/c}/\omega_t$

4. Attitude Maneuver Rate Estimation

In this section, attitude maneuver rate obtained by the proposed torque generation method is estimated under the rigid body approximation.

Using Newton-Euler's equations,

$$M = \frac{dh}{dt} + \omega_r \times h \quad (4)$$

where :

M : total torque acting on the system

h : angular momentum of the system

ω_r : angular velocity of despin body-fixed frame to the inertial frame

Take an average of one cycle of the sailcraft's spin,

$$\frac{dh}{dt} \approx 0 \quad (5)$$

Thus, Eq.(4) can be rewrite as:

$$\omega_r \approx \frac{M}{h} \quad (6)$$

Fig. 12 shows obtainable torque by the C.P.-C.M. offset method.

Estimated attitude maneuver rate ω_r at the Earth, Mars and Jupiter are shown in Table 1. Attitude maneuver rate of planned methods are approximately 1-3 deg/day, thus the proposed method is comparable to them for space exploration missions.

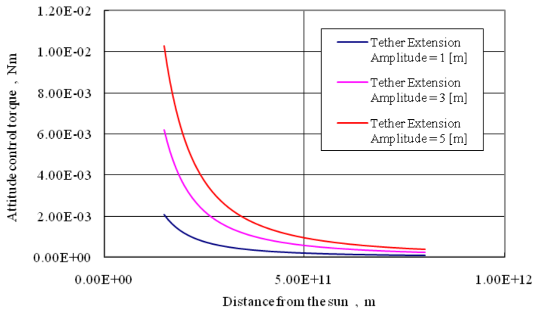


Figure 12 Torque by the C.P.-C.M. Offset

Table 1 Estimation of Attitude Maneuver Rate

		Tether Length Amplitude		
		1 [m]	3 [m]	5 [m]
Attitude Control Rate [deg/day]	Earth	11	35	58
	Mars	3.4	10	17
	Jupiter	0.40	1.3	2.2

$(\omega_{s/c} = 0.01[\text{rad/sec}],\ l_{sat} = 80[\text{m}])$

5. Attitude Dynamics under Solar Pressure

In this section, attitude dynamics of the tether-controlled spinning solar sail is investigated by numerical simulation under solar pressure with changing its tether length. Analytical model is as same as which was described in section 3.1. All sub-satellites' tethers were controlled sinusoidally.

Fig. 13 shows the trajectory of a head of normal vector to the sub-satellite plane. Sub-satellite plane can be inclined by the C.P.-C.M. offset torque, but nutation and out of membrane vibration also occurs. This result suggests some passive or active nutation damping method is needed for attitude maneuver of the sailcraft.

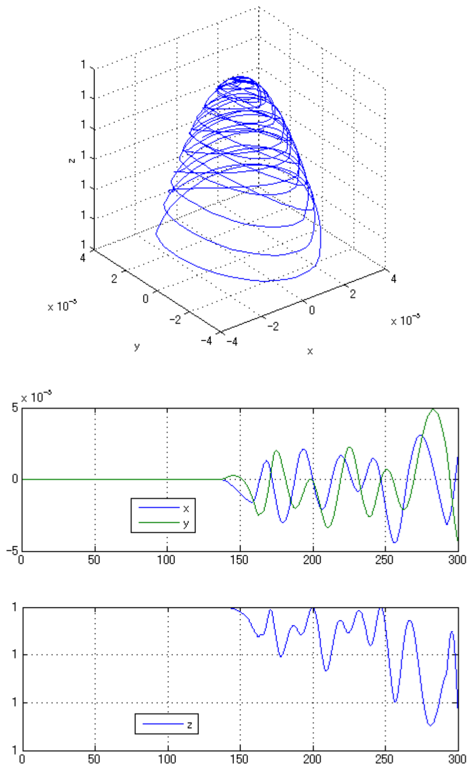


Figure 13 Time History of Normal Vector to Sub-Satellite Plane
(Top: 3-D Graphics, Bottom: Component Graphs)

6. Conclusion

C.P.-C.M. offset torque generation method for attitude maneuver of tether-controlled spinning solar sail was proposed. Numerical simulations on dynamic behavior during tether length control were conducted with a simple mass-spring-damper model. The parameter dependencies of the tether length controllability were investigated for excitation vibration between sub-satellites and membrane. Rate of attitude maneuver using C.P.-C.M. offset torque was estimated under solid body assumption and suggested that comparable to the other methods. Numerical simulation of attitude maneuver by controlling tether length was conducted under solar pressure. From the simulation result, vibration of the membrane and nutation motion of the sailcraft were found. Some passive or active damping methods are under study to suppress it.

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