Dynamics of a Solar Power Satellite Composed of Multi-bus with Panels for Power Generation and Transmission

Kei Senda*1, Kosei Ishimura*2, Itsushi Takemoto*1,
*1 Kanazawa University, Kakuma-machi, Kanazawa, Ishikawa 920-1192, Japan
*2 Hokkaido University, Kita-ku, Sapporo, Hokkaido 060-0814, Japan

Abstract

This study evaluates stability of the design points of solar power satellites (SPS’s) proposed by USEF (Institute for Unmanned Space Experiment Free Flyer) in 2006. The SPS consists of the power generation and transmission panel part, the distributed bus part, and tethers connecting them. For the original system and three types of static balance systems, the equilibrium points are found and their stabilities are evaluated by using the principle of minimum potential energy and the numerical simulations. The original system has the stable equilibrium point whereas the panel part is bent. One of the static balance systems has the stable equilibrium point at the design point where the panel part is flat. Then the static balance system is analyzed again as a flexible multi-body system by numerical simulation. The analysis using a flexible body is slightly different from that of rigid body when the elastic deformation becomes remarkable.

1 Introduction

A space solar power system (SSPS) is investigated as a new energy source that is expected as an alternative to fossil fuel.1]2] We generate electric power by the SSPS, e.g. generate electricity using solar power satellites (SPS’s), convert it into microwave or laser, transmit it to antennas on the earth, re-convert it into electricity using the on-ground power receiving plants, and supply the electric power to cities. We need to discuss system feasibility about architecture and dynamics because a typical SSPS is several kilometers long.

By using the principle of minimum potential energy and a numerical simulator, this study evaluates stabilities of equilibrium points of the original and some derived static balance SPS’s proposed by USEF (Institute for Unmanned Space Experiment Free Flyer) in 2006.

In the principle of minimum potential energy, we consider a sum of the potential energy of gravity, the potential energy of centrifugal forces, and the strain energies in panels and tethers. The equilibrium point is calculated by the Newton-Raphson method. The stability of the equilibrium point is evaluated through the eigen-values of second derivatives of total potential energy.

In the numerical simulator, we model a structurally flexible satellite as the multi-body system that is composed of rigid bodies connected with others by springs.
Body $j$. The $r_j$ is the position vector of $O_j$ from $O_I$, $r_O$ is the position vector of $O_O$ from $O_I$, and $r_{j,O}$ is the position vector of $O_j$ from $O_O$. The vector $\omega_j$ expresses the angular velocity of $\Sigma_j$ from $\Sigma_I$, the vector $\omega_O$ expresses the angular velocity of $\Sigma_O$ from $\Sigma_I$, and the vector $\omega_{j,O}$ expresses the angular velocity of $\Sigma_j$ from $\Sigma_O$.

2.2 Modeling and outline of SPS’s

2.2.1 Modeling and outline

The feasibility of a ‘06 USEF SPS (Fig. 2) is examined. The feature of the system dynamics of the SPS is as follows. The whole system consists of the power generation and transmission part located near the earth in parallel to the surface, the distributed bus part located on reverse-side, and the tethers connecting them. The power generation and transmission part is composed of the power generation and transmission panels, which generates the electric power by the solar cells and transmits the microwave by the phased array antenna facing on the earth. The whole system consists of 25 homogeneous basic units being connected each other. Each basic unit is composed of the power generation and transmission panel, the bus, and the four tethers. Each basic unit can work as a SPS. The outline of the system is listed below.

**Orbit**: geostationary orbit (GEO)
**Power generation scale**: 1 GW
**Power transmission method**: microwave
**Satellite configuration**:
(a) passive gravity gradient stabilization

![Fig. 1: Satellite modeled by rigid multi-body system, and coordinate frames](image1)

**Fig. 1**: Satellite modeled by rigid multi-body system, and coordinate frames

![Fig. 2: ‘06 USEF SPS model](image2)

**Fig. 2**: ‘06 USEF SPS model

**2.2.2 Derived ’06 USEF SPS Systems**

The above system is called the original system in this study. The left figure of Fig. 3 (a) is the system seen from $-x$ direction. The original system has the problem that the panel part is bent as shown in the right of Fig. 3 (a) because moments of forces are applied to hinges between lines. This study discusses the reason why the moment of force is generated that causes the deformation of the panel part. Both of the gravity and the centrifugal force are statically applied to each part as illustrated in Fig. 4. The gravity and the centrifugal force do not balance in the unit being outside the orbital plane because the gravity is pointing the geocentric but the centrifugal force is parallel to the surface, the distributed bus part located near the earth in parallel to the orbital plane. Therefore, the external force $f_{Bj}$ and $f_{pj}$ act on each part. The moments of forces about hinges $k$ and $j$ are:

$$
\begin{align*}
\tau_{Hk} &= \tau_{Hkr,pk} \times f_{pk} + \delta_{kr} \times f_{Bk} \\
\tau_{Hj} &= \tau_{Hjr,pj} \times f_{pj} + \delta_{jr} \times f_{Bj} \\
&+ \left( \tau_{Hjr,pj} - \tau_{Hjr,pj} \right) \times f_{Hk}
\end{align*}
$$

(1) (2)

It is inconvenient that the panel part is bent by the moments of forces. The following static balance systems (1-
Equilibrium points of the original and some derived static balance systems

1), (1-2), and (2) are designed, where the mass distribution and/or the position arrangement of the buses are modified to avoid this inconvenience. These systems are summarized as follows.

The design is modified as Fig. 3 (b) so that the system is statically balanced (at an equilibrium point) when it is at the design point. The moment of force about the hinge becomes 0 when the line of action of the resultant force \( f \) on the unit runs through the hinge. Accordingly, the modified system would not result in the bending panel part. The buses in line 1, line 2, and line 3 are modified as

\[
m_{B1} = 2.33 \times 10^4\ [kg], \quad m_{B2} = 7.13 \times 10^4\ [kg], \quad \text{and} \quad m_{B3} = 9.09 \times 10^4\ [kg]\]

in mass, respectively. Other buses in line 4 and line 5 are symmetrical to line 3. This system is called the static balance system (1-1).

The moment of force about the hinge becomes 0 when the tether lengths are modified as Fig. 3 (c). The tethers in line 1, line 2, and line 3, respectively, are

\[
l_1 = 2.14 \times 10^3\ [m], \quad l_2 = 6.43 \times 10^4\ [m], \quad \text{and} \quad l_3 = 7.85 \times 10^4\ [m]\]

long, and the other tethers in line 4 and line 5 are symmetrical to line 3. This system is called the static balance system (1-2).

However, the numerical simulation has shown that the design point is not stable by considering slack of tethers. Then, the positions of the buses are modified again to make the design point be the true equilibrium point where the tethers do not slack. The buses in line 1, line 2, and line 3, respectively, are at \([-747.0, -3735]\), \([-425.5, -4735]\), and \([0.000, -6734]\) [m] in \( y \) and \( z \) directions, and the other buses in line 4 and line 5 are symmetrical to line 3. This system shown in Fig. 3 (d) is called the static balance system (2).

The numerical simulations have shown that the design points in the static balance systems (1-1) and (1-2) are not stable by considering slack of tethers [6], though the simulation results are omitted. The design point in the static balance system (2) is stabilized without slack of tethers as follows.

3 Stability Analysis of Equilibrium Point Using Potential Energy

The potential energy, which is caused by gravitational force and centrifugal force, is considered as well as strain energy of panels and tethers. The total potential energy is defined as the sum of these potential energies. The equilibrium point is calculated by applying the Newton-Raphson method to the first derivative of total potential energy. To evaluate the stability of the equilibrium point, eigen-values of second derivatives of total potential energy are calculated. If all signs of the eigen-values are positive, the equilibrium point is stable.
following assumptions are introduced:

1. The size of satellite is so small compared to orbital radius that the higher orders of these terms can be neglected.
2. The displacement along x axis is assumed to be uniform. Therefore, the deformation in y - z plane is considered.
3. The orbit is assumed to be circular.

3.1 Definition of the symbols and models

In this section, we treat five panels shown in Fig. 2 along the same line as one panel part. The rotation angle of each panel part \( j (= 1, \ldots , 5) \) around \( O_i \) axis relative to \( \Sigma_O \) is described as \( \theta_j \). In the same way, we treat five buses along the same line as one bus part. The subscript corresponds to the line number shown in Fig. 2. The configuration of the panel and bus parts is shown in Fig. 4. Superscript \( O_i \) indicates that the variables are described in the coordinate frame \( \Sigma_O \).

3.2 Gravitational and centrifugal potential energies

Under the assumptions 1 and 3, The general gravitational and centrifugal potential energies of a rigid body are approximated as follows.

Gravitational potential energy:

\[
U_j^{(g)} = - \frac{\mu}{r_O} \left[ m_j \left\{ \frac{1}{2} \left( \frac{\sigma_{j,1}\sigma_{j,1} + \sigma_{j,2}\sigma_{j,2} - 2\sigma_{j,3}\sigma_{j,3}}{r_O} \right) + \frac{1}{2} \sigma_{j,1} \sum \delta_{j,1} \right\} + \frac{1}{2} \sigma_{j,1} \sum \delta_{j,1} \right] + \frac{3}{2} \sum \left( \sigma_{j,21}^2 I_{j,11} + \sigma_{j,22}^2 I_{j,12} + \sigma_{j,33}^2 I_{j,13} \right)
\]  

(3)

Centrifugal potential energy:

\[
U_j^{(c)} = - \frac{1}{2} \omega^2 m_j \left\{ \frac{1}{2} \sigma_{j,1} + \frac{1}{2} \sigma_{j,2} - 2 \sigma_{j,3}\right\} + \frac{1}{2} \sigma_{j,1} \sum \delta_{j,1} \sum \delta_{j,1} + \frac{3}{2} \sum \left( \sigma_{j,21}^2 I_{j,11} + \sigma_{j,22}^2 I_{j,12} + \sigma_{j,33}^2 I_{j,13} \right)
\]  

(4)

By omitting the constant term, the sum of gravitational and centrifugal potential energies for No. \( j \) panel part is described as:

\[
U_j^{(g+c)} = - \frac{1}{2} \omega^2 m_j \left\{ \frac{1}{2} \sigma_{j,1} + \frac{1}{2} \sigma_{j,2} - 2 \sigma_{j,3}\right\} + \frac{3}{2} \sum \left( \sigma_{j,21}^2 I_{j,11} + \sigma_{j,22}^2 I_{j,12} + \sigma_{j,33}^2 I_{j,13} \right)
\]  

(5)

In the same way, the sum of gravitational and centrifugal potential energies for No. \( j \) bus part is described as:

\[
U_j^{(g+c)} = - \frac{1}{2} \omega^2 m_j \left\{ \frac{1}{2} \sigma_{j,1} + \frac{1}{2} \sigma_{j,2} - 2 \sigma_{j,3}\right\} + \frac{3}{2} \sum \left( \sigma_{j,21}^2 I_{j,11} + \sigma_{j,22}^2 I_{j,12} + \sigma_{j,33}^2 I_{j,13} \right)
\]  

(6)

3.3 Strain energy

At first, the strain energy of tethers between the panels and buses in line \( j \) are derived. The \( \delta_{jl} \) and \( \delta_{jr} \) indicates the position vectors from left and right ends of panel and bus as shown in Fig. 4. These vectors are described as:

\[
\delta_{jl} = r_{Bj,O} - (r_{Pj,O} + r_{Hj,p})
\]

\[
\delta_{jr} = r_{Bj,O} - (r_{Pj,O} + r_{Hj,p})
\]

(7)

where \( L_x, L_y, L_z \) are the length of each panel along \( x, y, z \) axes, respectively. Therefore, strain energy of tethers is described as:

\[
U_j^{(th)} = \left\{ \begin{array}{ll}
0 & (\delta_{jl} < l_{n,jl}) \\
10 \times \frac{1}{2} k_{th,jl} (\delta_{jl} - l_{n,jl})^2 & (\delta_{jl} \geq l_{n,jl})
\end{array} \right.
\]

(8)

\[
U_j^{(th)} = \left\{ \begin{array}{ll}
0 & (\delta_{jr} < l_{n,jr}) \\
10 \times \frac{1}{2} k_{th,jr} (\delta_{jr} - l_{n,jr})^2 & (\delta_{jr} \geq l_{n,jr})
\end{array} \right.
\]

(9)

3.4 Total potential energy

The total potential energy is described in terms of the above potential energies as:

\[
U_{total} = \sum_{j=1}^{5} (U_j^{(g+c)} + U_j^{(th)}) + \sum_{j=1}^{5} (U_j^{(th)} + U_j^{(th)})
\]

(11)

3.5 Procedure of analysis

Under the assumption 2 and constraint condition, which the center of mass of the satellite is fixed to the origin of orbital coordinate frame, following 23 variables are independent.

\[
x = [ \theta_1 \cdots \theta_5 \sigma_{P2,0,y} \cdots \sigma_{TP5,0,y} \sigma_{TB1,0,y} \cdots \sigma_{TB5,0,y} \sigma_{TP2,0,z} \cdots \sigma_{TP5,0,z} \sigma_{TB1,0,z} \cdots \sigma_{TB5,0,z} ]^T
\]

(12)
We call \( x \) state variable. From the above constraint condition, the position vector of panel part 1 is described as:

\[
O_{TP1,O} = \frac{-1}{m_{P1}} \left( \sum_{j=2}^{5} m_{Pj,O} O_{TPj,O} + \sum_{j=1}^{5} m_{Bj,O} O_{TBj,O} \right)
\]

(13)

The following first and second derivatives of total potential energy are derived analytically.

\[
f(x) = \left[ \frac{\partial U_{total}}{\partial x_1} \ldots \frac{\partial U_{total}}{\partial x_{23}} \right]^T
\]

(14)

\[
J(x) = \left[ \frac{\partial f}{\partial x_1} \ldots \frac{\partial f}{\partial x_{23}} \right]
\]

(15)

The equilibrium point \( x^* \) is searched by applying Newton-Raphson method to the first derivative of total potential energy \( U_{total} \). Following calculation is iterated until \( ||f(x_k)|| \) decreases within an allowable error.

\[
x_{k+1} = x_k - J^{-1}(x_k) f(x_k)
\]

(16)

The eigen-values of \( J(x^*) \) are used to judge if the total potential energy has the minimum value at the obtained equilibrium point. If all eigen-values are positive, the total potential energy has the minimum value at the equilibrium point. Therefore, the equilibrium point is stable. If the above iterative calculation could not converge, equilibrium point might not exist. In such a case, following additional calculation is carried out to confirm the non-existence of equilibrium point.

At first, a tentative equilibrium point is searched under the assumption that tethers can exert resorting force against compression. Then, the tension of tether is compressed, spring constants of compressed tethers are checked whether the tether is compressed or not. If some tethers are compressed, a tentative equilibrium point is searched. If the above iterative calculation could not converge, equilibrium point might not exist. In such a case, following additional calculation is carried out to confirm the non-existence of equilibrium point.

3.6 Results of analysis

Through the analysis, the equilibrium point is obtained. At the equilibrium point, rotation angle of each panel part and displacement of panel parts and bus parts from the no-strain state are shown in the following.

Result of '06 USEF original SPS system

The right figure of Fig. 3 (a) is the equilibrium point. The rotation angles of panel parts are:

\[
\begin{bmatrix}
\theta_1 & \theta_2 & \theta_3 & \theta_4 & \theta_5 \\
\end{bmatrix} = \begin{bmatrix}
0.053 & 0.031 & 0.000 & -0.031 & -0.053 \\
\end{bmatrix} [\text{rad}]
\]

(17)

The displacements of panel parts along the \( y,z \) axes from the no-strain state, \( u_{Pj} \), are symmetric with respect to line 3.

\[
\begin{bmatrix}
o_{u_{P1}} & o_{u_{P2}} & o_{u_{P3}} \\
\end{bmatrix} = \begin{bmatrix}
0.56 & 0.11 & 0.00 \\
-13.62 & 6.30 & 13.64 \\
\end{bmatrix} [\text{m}]
\]

(18)

The elongation of each tether is as follows.

\[
\begin{bmatrix}
u_{11}^{(th)} & v_{22}^{(th)} & u_{31}^{(th)} & u_{41}^{(th)} & v_{51}^{(th)} \\
u_{1r}^{(th)} & u_{2r}^{(th)} & u_{3r}^{(th)} & u_{4r}^{(th)} & u_{5r}^{(th)} \\
\end{bmatrix} = \begin{bmatrix}
5.4 & 4.9 & 6.0 & 7.0 & 6.6 \\
6.6 & 7.0 & 6.0 & 4.9 & 5.4 \\
\end{bmatrix} \times 10^{-3} [\text{m}]
\]

(20)

All tethers are not slacked at the obtained equilibrium point. This equilibrium point is stable because all eigenvalues of \( J \) are positive.

Result of static balance system (1-1)

In this system, the calculation for search of equilibrium point cannot converge. Under the assumption that tethers can exert resorting force against compression, a tentative equilibrium point is as follows.

Fig. 3 (b) is the tentative equilibrium point. The rotation angles of panel parts are:

\[
\begin{bmatrix}
\theta_1 & \theta_2 & \theta_3 & \theta_4 & \theta_5 \\
\end{bmatrix} = \begin{bmatrix}
0.000 & 0.000 & 0.000 & 0.000 & 0.000 \\
\end{bmatrix} [\text{rad}]
\]

(21)

The displacements of panel parts along the \( y,z \) axes from the no-strain state, \( u_{Pj} \), are symmetric with respect to line 3.

\[
\begin{bmatrix}
o_{u_{P1}} & o_{u_{P2}} & o_{u_{P3}} \\
\end{bmatrix} = \begin{bmatrix}
0.00 & 0.00 & 0.00 \\
0.00 & 0.00 & 0.00 \\
\end{bmatrix} [\text{m}]
\]

(22)

The elongation of each tether is as follows.

\[
\begin{bmatrix}
u_{11}^{(th)} & v_{22}^{(th)} & u_{31}^{(th)} & u_{41}^{(th)} & v_{51}^{(th)} \\
u_{1r}^{(th)} & u_{2r}^{(th)} & u_{3r}^{(th)} & u_{4r}^{(th)} & u_{5r}^{(th)} \\
\end{bmatrix} = \begin{bmatrix}
6.0 & 12.9 & 9.7 & 2.3 & -1.0 \\
-1.0 & 2.3 & 9.7 & 12.9 & 6.0 \\
\end{bmatrix} \times 10^{-3} [\text{m}]
\]

(24)

The elongation of two tethers is negative. These tethers should be slacked and spring constants of slacked tethers should be set to zero. The equilibrium point is recalculated with the initial condition of tentative equilibrium point under above assumption that spring constants of slacked tethers are zero. However, the valid equilibrium point cannot be found. Therefore, the equilibrium point could not exist for this system.
The displacements of panel parts along the no-strain state, \( \mathbf{u}_{Pj} \), are symmetric with respect to line 3.

\[
\begin{bmatrix}
    O \mathbf{u}_{P1} & O \mathbf{u}_{P2} & O \mathbf{u}_{P3}
\end{bmatrix}
\]

\[
= \begin{bmatrix}
    0.00 & 0.00 & 0.00 \\
    0.00 & 0.00 & -0.01
\end{bmatrix} \text{ [m]}
\]

(26)

The elongation of each tether is as follows.

\[
\begin{bmatrix}
    u_{1l}^{(th)} & u_{2l}^{(th)} & u_{3l}^{(th)} & u_{4l}^{(th)} & u_{5l}^{(th)} \\
    u_{1r}^{(th)} & u_{2r}^{(th)} & u_{3r}^{(th)} & u_{4r}^{(th)} & u_{5r}^{(th)}
\end{bmatrix}
\]

\[
= \begin{bmatrix}
    2.6 & 16.9 & 15.0 & 3.0 & -0.5 \\
    -0.5 & 3.0 & 15.0 & 16.9 & 2.6
\end{bmatrix} \times 10^{-3} \text{ [m]}
\]

(28)

The elongation of each tether is as follows.

\[
\begin{bmatrix}
    u_{1l}^{(th)} & u_{2l}^{(th)} & u_{3l}^{(th)} & u_{4l}^{(th)} & u_{5l}^{(th)} \\
    u_{1r}^{(th)} & u_{2r}^{(th)} & u_{3r}^{(th)} & u_{4r}^{(th)} & u_{5r}^{(th)}
\end{bmatrix}
\]

\[
= \begin{bmatrix}
    4.8 & 8.5 & 11.8 & 3.4 & 2.8 \\
    2.8 & 3.4 & 11.8 & 8.5 & 4.8
\end{bmatrix} \times 10^{-3} \text{ [m]}
\]

(32)

All tethers are not slacked at the obtained equilibrium point. This equilibrium point is stable because all eigenvalues of \( \mathbf{J} \) are positive.

### 3.7 Comparison with numerical simulations

The analyzed results using the principle of minimum potential energy are compared with numerical simulations. A numerical simulation of the original system with some damping obtains a stationary state in orbit as time goes, which can be considered as a statically stable state. The obtained state in Fig. 3 is as same as the result in section 3.6.

The simulation result of the static balance system (1-2) is illustrated every 7000 [s] in Fig. 5. It is not possible to maintain the stability at the design point because tethers slack, and the system collapses as time goes. The instability is caused by bus position shifting since the slack tethers cannot generate compression forces. The static balance system (1-1) is also unstable and cannot maintain the stability at the design point.

A numerical simulation shows that the static balance system (2) converges to the stationary state at the design point after perturbation torques are applied in hinges. Hence, stability of the design point can be confirmed, whereas its illustration is omitted.

### 3.8 Summary of the results

The numerical simulations and the obtained results using the principle of minimum potential energy agree with each other. As a result, it can be said that both analysis methods are valid.

The original system has the stable equilibrium point where the panel part is bent. At the equilibrium state, the center of mass of panel part 3 (center) displaces about 26 [m] to the nadir with respect to that of panel part 1 (tip).

For static balance system (1-1), (1-2), tentative equilibrium states are found under the assumption that tethers can exert resorting force against compression. If
spring constants of slacked tethers are set to zero, however, no valid equilibrium state are found near the tentative equilibrium state for static balance system (1-1), (1-2).

The static balance system (2) has the stable equilibrium point at the design point where the panel part is flat.

4 Flexible Body Analysis on ’06 USEF SPS

4.1 Outline of method of flexible body analysis

When the numerical simulator calculates the external forces, it is necessary to know the position and orientation of each part in flexible bodies. According to the definition of mechanical analysis software ADAMS [7, 8, 9], the position and orientation in flexible body is considered as the sum of the rigid body motion and that caused by the elastic deformation as illustrated in Fig. 6.

Nomenclature for flexibility is given below. The Σj is the reference coordinate frame used for flexibility description in ADAMS, Σjn is a node coordinate frame in each node of a flexible body, and Σjnorig is a coordinate frame in each node when the flexible body is not deformed. The ujn is an elastic deformation vector of the flexible body from the origin Σjnorig. The position of Σjn is described as

\[ r_{jn,O} = r_{j,O} + s_{jn} + \Phi_{jn} q \] (33)

where the elastic displacement ujn is given by a mode representation, Φjn is a modal matrix for translation, and q is a vector of the modal coordinates. The node velocity of the flexible body is obtained by the following equation.

\[ \frac{dr_{jn,O}}{dt} \bigg|_O = \frac{d(r_{j,O} + s_{jn} + \Phi_{jn} q)}{dt} \bigg|_O \] (35)

The attitude of node coordinate frame Σjn from the orbit coordinate frame ΣO is represented by a direction cosine matrices as:

\[ ^O R_{jn} = ^O R_j ^j R_{jnorig} jnorig ^j R_{jn} \] (36)

where the rotational displacement is also given by the following mode representation, and \( \Psi_{jn} \) is a modal matrix for rotation:

\[ ^O R_{jn} = ^O R_j ^j R_{jnorig} [I + [\Psi_{jn} q \times]] \] (37)

4.2 Analysis on flexible body model

The analysis model (Fig. 7) with 3 × 3 units is designed as well as the static balance system (2) from the original ’06 USEF SPS that stabilizes the design point avoiding the tether slack. Fig. 8 shows the simulation result of the system behavior every 60000 [s] where the rigid multi-body system is used as well as the previous analysis. It is confirmed that the panel part is not bent and the static balance condition is kept.

The model with the flexible panels is used for an analysis. Fig. 9 shows the simulation result of the system behavior 0 [s] and 180000 [s]. The displayed contour shows the elastic displacement of panel from the initial flat plane before deformation. In each panel, the four
corners are pulled in the direction toward the bus, and the center part is pulled in the direction toward the geocentric. The static balance system is designed so that the moment of force about the hinge between units becomes 0. However, moments of force are not 0 excluding hinges. The moments of force deform the panel when each panel is modeled as a flexible body. There is a 5 [m] difference in z direction between the center and the corners of the panel.

Fig. 10 shows the equilibrium point of the rigid body analysis and that of the flexible body analysis. Because each panel is bent, its mass center moves toward the geocentric and the bus shifts in opposite direction. Both ends of the panel part move in the direction toward the geocentric. Therefore, the bus parts in lines 1 and 3 get away from line 2.

These show the necessity of the flexible body analysis. It is necessary to discuss system design using the flexible multi-body system, e.g. to increase number of tethers to avoid panel bending, to confirm the panel strength being enough to the load, etc.

5 Conclusion

This study has discussed the equilibrium points and their stability of the original and the derived static balance SPS’s by using the principle of minimum potential energy and the numerical simulations. The following results have been shown. The two analysis methods are both valid. The original system has the stable equilibrium point whereas the panel part is bent. The static balance system (2) has the stable equilibrium point at the design point where the panel part is flat. If the static balance system is designed by a rigid body, the analysis using a flexible body may have a result different from that of rigid body when the elastic deformation in the panel becomes remarkable. Therefore, it will be necessary to design SPS’s considering structural flexibility more accurately in the future.

Reference