Dynamic Behavior of Spinning Square Solar Sail

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Spinning solar sail is expected as a future space exploration system. The dynamic deformation of the sail membrane should be considered sufficiently in the design of the spacecraft as well as the sail membrane itself. In this presentation, the motion of a spinning square solar sail is illustrated to help the understandings of the dynamics of the solar sail, and the design issue of the membrane of a spinning solar sail is summarized.

Introduction

The spin-stabilized solar sail has been studied by JAXA and universities in Japan. They say that the deployment and the shape keeping of the sail membrane assisted by the centrifugal force has some advantage over that by the extension of the radial masts attached to the membrane when the sail is large, e.g. over 100m. In this case, the technology of the spin deployment of large thin membrane is the key to the future deep space exploration by the solar sail.

There are, however, various problems to be solved in the design process of the spacecraft. In this paper, we focus on the design of the sail membrane including the deployment dynamics, and explain the characteristics of spinning square solar sail with numerical examples of a 20m-sized sail. Finally, the remaining problems are listed.

Square sail

Configuration of the sail

The sail model considered in this paper is illustrated in the followings.

As in Fig. 1, four trapezoidal membranes, called “petal” in this paper, are connected with rectangular membranes, called “bridge”, to form a square-like membrane structure. The membrane structure acts as the sail against the solar radiation pressure. The sail is linked with the spacecraft bus by the tethers called “center tether” as in Fig. 2. Four tip masses are linked with the tethers called “tip tether”. The spacecraft spins on orbit to deploy the sail and make it maintain its shape by the centrifugal force. These tip masses assist the spin deployment of the sail with their own centrifugal forces.

Fold and deployment of the sail

The sail is folded to the launch configuration through two steps. In the first step, the sail as Fig. 1 is folded as Fig. 3(a). In this state, the folded membrane forms four branches. The membrane is then wrapped around the spacecraft bus and held by four guide bars, as in Fig. 3(b),
which illustrates the launch configuration of the spacecraft. The deployment goes through the opposite procedure. In the first stage, the guide bars rotate around the spacecraft bus slowly. Thus four branches of the folded membrane are extracted steadily and extend by the centrifugal force. When the rotation of the guide bar is completed, the membrane forms the configuration as in Fig. 4. The guide bars stop that the membrane deploys into the sail configuration as in Fig. 1.

In the second stage, each guide bar fall down and the membrane deploys out. Thus the spinning square solar sail considered in this paper has two stages in the deployment procedure.

Intrinsic problems of square sail

Considering the sequence of the event, i.e. the first stage of the deployment, the second stage, the stabilization of the sail shape, and the navigation with the attitude maneuver, you will find several problems about (1) the support structure and the deployment mechanism of the sail, (2) the sail structure itself including the tethers and the bridges, and (3) the control of the shape and the attitude of the sail. In this paper, we focus on the second one, i.e. the problem in the sail structure. It is important to predict the dynamic behavior of the sail in the deployment process as well as the sail actually behaves appropriately, i.e. no trouble to prevent the deployment occurs in the process. Generally speaking, one will have the difficulty in the determination of the design parameters if the prediction technology is not developed well. The second stage of the deployment of the square sail is the case. The important points in the second stage are shown in the followings.

Mathematical model

It is not adequate to evaluate the performance of the deployment, the quasi-static shape of the sail after the deployment, and the following performance of the sail in the attitude maneuver of the spacecraft only with the ground experiments. In fact, there has not been developed the experimental method of the deployment of large membrane to simulate the behavior of the membrane under the micro-gravity and the vacuum environment. In such a case, the numerical simulation is necessary to complement the evaluation. Generally, the mathematical model of mechanical system should be defined to achieve the objectives of the analysis. In our case, however, we may design such a sail deployment system that the ambiguous effect of any factor will be minimized. Then, we design the system in detail so that it is feasible even under the worst case of the ambiguous effects. The mathematical model may neglect the minor effect of such factors to reduce the computation cost. In case of solar sail, the local wrinkle of the membrane may decrease the performance of the propulsion. The spring effect and the hysteresis of the fold line may also give undesirable influence on the deployment dynamics and the equilibrium shape after the second stage. The effects of the wrinkle and the fold line depend on the product error which distributes whole of the membrane. We can hardly measure all of the error. Therefore, such effects can not be estimated precisely. In case of our square sail, such effects should be reduced by linking the appropriate amount of the tip mass so that the performance of the deployment is improved. Then, we can evaluate the performance of the sail without programming the local buckling and the bending of the membrane.

Such a model reduction is required to shorten the design period. The geometrical relations also have to be simplified in the finite element analysis of the deployment of large membrane for this requirement. For example, the number of the fold line can be modified to be smaller than the flight model. There may be various discussions referring to the validity of such a simplification. The control model must be simpler than the detailed dynamics model in order to realize the on-board processing as well as to shorten the development period of the control law. The model reduction technique should be applied to construct the control model.

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within several seconds, but the in-plane oscillation continues for a while. The oscillation is almost suppressed about a thousand seconds after the second stage starts because of the damping of the center tethers.

Fig. 6 shows the distribution of the strain energy density. The red area represents higher density, and the blue one represents lower density. At the time $t = 2.0\text{sec}$ (Fig. 6(a)), the energy concentrates at some specific area where the objects such as solar cells are attached to the membrane. But after a while, the almost all area of the petal has low energy and repeats the taut state and the slack state. The energy concentrates along the diagonal line of the square sail because the centrifugal force of the tip mass is much larger than that of the petal membrane. This figure suggests that some model reduction is possible in the deployed state when enough time, e.g. 2000sec, elapses after the second stage starts.

Fig. 6 Strain energy density distribution

(a) $t=2.0\text{sec}$ (b) $t=1000\text{sec}$ (c) $t=2000\text{sec}$

As in Fig. 5, the radius of the petal oscillates in the beginning of the second stage. Fig. 7 and Fig. 8 show the change of the radius of the petal and the kinetic energy of the whole system, respectively. At first, the kinetic energy decreases and the radius increases. But the energy increases at $t = 2.1$, and the radius decreases. This means that the membrane vibrates in out-of-plane direction as well as it spreads in the horizontal plane, and it shrinks back. This result means that the fold pattern and the deployment method considered here do not realize smooth or “natural” deployment of the membrane. Fig. 9 shows the change of the radius in case of so-called “spiral” folding as in Fig. 10. In this case, the radius increases monotonically and the membrane does not shrink back. In other words, the deployment of the spirally folded membrane is more “natural” than that of the square sail. Such a view point can be useful for the evaluation of the performance of the deployment.

Fig. 7 Radius of petal in the beginning of second stage

Fig. 8 Kinetic energy in the beginning of second stage

Fig. 9 Change of radius in case of spiral folding

Fig. 10 Spin deployment of spirally folded membrane

Fig. 11 shows the change of the spin rate. The solid line represents the case in which the number of fold line is 18, the same as the flight model, while the dotted line represents the case of 8 fold lines. Indeed there is the difference, but the difference is small and the perspective of the deployment behavior is similar to each other. Thus the simplification of the fold pattern is available for the rough understandings of the deployment motion.

Fig. 11 Change of radius in case of spiral folding

In the above results, we should take into account the fact that the membrane does not bear the compressive load. But we do not have to consider the bending rigidity of the fold line and the out-of-plane deformation at the wrinkle. If you need to analysis the detail of the deformed shape, especially the out-of-plane deformation, you should employ the shell element to model the
membrane. You can use simpler element, i.e. the tension field element if you do not need the detailed shape and you like to reduce the computation time.

**In-plane stress during the deployment**

If the spin rate is not controlled actively during the deployment, which is our case, the membrane can be subjected to some impulse load at the moment that the membrane deploys out. It is important to predict such an impulse load for the strength design of the membrane. We can obtain the time history of the tension of the membrane and tethers by numerical simulation. But they depend on the geometry of the finite element division and the time step width. Therefore, it is difficult to use the numerical result for the strength design only by multiplying the safety factor to the result. We should estimate the upper bound of the stress applied to the membrane and the tethers. One example of the estimation method of the bound is as follows: In case of our square sail, the tip mass is subjected only to the tension of the tip tethers. Let $P_o$ denote the maximum value of the component of the linear momentum of the tip mass in the direction of the tip tether. Then, the impulse load testing of the tether is conducted as follows. A small weight is attached to one end of the tether, and the other is fixed. The weight is lifted up to the height of $h_o$ (the tether is slacked), and then it is dropped to investigate the strength against the impulse load. $h_o$ is determined so that the linear momentum is $\alpha P_o$ ( $\alpha$ is the safety factor) at the moment when the tension is applied to the tether (i.e. $\alpha P_o = m\sqrt{2gh_o}$). In this testing, the impulse load is overestimated because the end of the tip tether is not fixed in the deployment of the sail. In the impulse load testing of the membrane, the height $h$ is determined so that the ratio of the tension of the tip tether to that of the membrane in the simulation is the same as the ratio of the linear momentum of the tip tether to that of the membrane in the testing. Indeed this testing method has a few theoretical problems, but it can be one of the methods to reflect the numerical result to the testing.

**Residual vibration after deployment**

If the deployment speed is not controlled, we should estimate the convergence time of the residual vibration after the second stage because it has an impact on the consequent event, e.g. attitude maneuver. If the time is ambiguous, we can not design the sequence of event. Of course, we only have to wait for enough time until the vibration is suppressed by the damping of the membrane and the tethers if we can not estimate the convergence time. But we should keep an approximate value of the time. Fig. 12 shows an example of the change of the radius of the membrane and the angular velocity of the spacecraft bus during the second stage. In this example, the damping of the petal, bridge, and the tip tether is 0, and that of the center tether is assumed to be very small compared with the experimental result, but not 0 ($\sigma = \eta E \varepsilon$ with $\eta = 2.0 \times 10^{-8}$ sec$^{-1}$). The vibration converges in a short period, which means that small damping of the center tether is enough for the mission). The configuration of the center tether gives great influence on the suppression of the vibration. The configuration shown in Fig. 2 is designed to make the most of the damping of the tethers.

**Stress in deployed state**

Numerical results show that the tension is not always applied to the membrane after the residual vibration is suppressed. In fact the duration when the membrane wrinkles or slacks is much longer than that when the membrane is under tension. The membrane has in-plane and out-of-plane motion, and occasionally tensed because of the constraint by the center tethers and the tip tethers. The width of the bridge has a significant effect on this phenomenon. The bridge works so that the membrane is relaxed in the circumferential direction. Thus the membrane can hardly have the tension in that direction. The bridge is necessary to avoid the trouble which occurs when the circumferential length of the membrane is inadequate, e.g. caused by the product error of the shape of the membrane. The trouble is that the tension induced by the spin of the spacecraft bus is not transferred to the membrane and the membrane can not maintain its shape. We can hardly eliminate the product error, so we should keep the margin on the circumferential length of the membrane.

**Conclusion**

The overview of the deployment motion of the
spinning square solar sail and several problems on the design of the sail are presented. There are problems other than those mentioned above, e.g. the attitude motion of the spacecraft induced by the deflection of the sail membrane subject to the solar radiation pressure, the windmill effect by the solar radiation pressure, and the influence of the local deformation of the membrane on the acceleration of the spacecraft. The width of the bridge gives influence on the residual vibration after the deployment, which is not analyzed yet.

Actually, there remained lots of research topics in the dynamic deformation of the solar sail. We should solve each problem in the topics to realize the solar sail, and establish the design method of the solar sail.

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References

