Deployment Simulations of Space Webs

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ABSTRACT

The ESA Advanced Concepts Team has looked at the possibility to construct large space antennas and solar power systems by deploying and stabilising a large web in space. The idea originates from the Japanese "Furoshiki Satellite", which was deployed in space in January 2006. Because a complicated control system contributed to the chaotic deployment, ESA wants to take advantage of the centrifugal forces to deploy the space web in a way that requires less communication.

In this study a control strategy is presented, some LS-DYNA simulations of the deployment of space webs are performed, and it is suggested how to use user defined loads to do simulations using feedback control.

Keywords:

Space webs, Furoshiki, Centrifugal forces, Feedback control, User defined load

1 INTRODUCTION

Power generation (Solar panels), propulsion (Solar sails) and communication (Antennas) are some important applications for large deployable structures in space. The ESA Advanced Concepts Team has looked at the possibility of constructing large space antennas and solar power systems by deploying and stabilising a large web in space. The idea originates from the Japanese "Furoshiki Satellite".[1–3] The space web is composed of a large membrane or net held in tension by controlled corner satellites or by spinning the whole assembly. The large aperture of the "Furoshiki" can be used as a phased antenna or as a solar power satellite. An idea put forward by Kaya *et al.*[4] is to build up the antenna or solar power elements by robots that crawls on the web like spiders.

The difficulty in deploying a space web in a controlled manner was shown in the partly chaotic deployment during the Furoshiki experiment in January 2006. Therefore, a deployment that is easier to control is desirable. The ESA has investigated the possibilities to use centrifugal forces to deploy and stabilize the web.[5,6] Deployment using centrifugal forces have many advantages, e.g., the control can be achieved from the centre hub, all the significant forces are in the plane of rotation, both fast and slow deployment velocities are possible. Large structures stabilised by centrifugal forces have been considered for space applications since the early 1960s when the Astro Research Corporation analysed several spin-stabilised structures.[7] Nevertheless, the only successful deployment and control of a large spin-stabilised space structure is the Russian Znamya-2 experiment in 1993.[8]

To obtain a successful deployment a smart control strategy must be used. The control strategy proposed for circular membranes by Melnikov and Koshelev[8] is here investigated analytically for quadratic space webs. It is also discussed how to implement the control algorithm using the User defined load in LS-DYNA.[9]

2 CONTROL STRATEGY

A stable deployment is obtained if the centrifugal force, which is directed radially, is much greater than the Coriolis and inertial forces.[8] The deployment can be controlled in different ways. The control parameters could be the torque, M, the current length of the tether, L, the angular velocity of the centre hub, ω, or the force that resists the deployment of each segment, N.

Several, more or less successful, control strategies have been described in literature. Salama *et al.*[10] linearly increase the angular velocity ω from 0 to $\omega_{\max}$ during a time period of Δt, and then keep it constant at $\omega_{\max}$. Melnikov and Koshelev[8] use the torque and the velocity of the cable being fed out as control parameters to deploy the reflector. They propose that the momentum should vary according to the law:

$$M = M_0 \left(1 - \frac{\omega}{\omega_0}\right) \tag{1}$$

where M_0 is the initial momentum applied to the centre hub and ω_0 is the initial angular velocity of the centre hub. A refined control strategy may be necessary to compensate for the gravity gradient.

3 CONTROL STRATEGY IN LS-DYNA

As can be seen from Eq. (1) the applied torque on the centre hub is dependent on its angular velocity. Feedback control is not trivial in LS-DYNA and a user defined load must be implemented. This is done by the command ∗USER_LOADING in the LS-DYNA code. LS-DYNA then calls for the Fortran subroutine *loadud* in which, e.g., displacements, velocities and accelerations of the nodes are known. The user can also send some parameters, in this case M_0 and ω_0 that are defined at the same time as ∗USER_LOADING. In the subroutine *loadud* the angular velocity is not known. However, the angular velocity can be computed from the velocity of one point on the centre hub according to $v = \omega r$ since the origin is fixed. Similarly, the torque to apply can be determined from the nodal forces according to $M = Fr$.

4 FINITE ELEMENT MODEL

An analytical model has been implemented in MATLAB. In parallell, a finite element model including a space web, corner masses and a central satellite has been implemented. The node and element geometry and connectivity are generated in MATLAB. The equations of motion are then solved in LS-DYNA[9] using the explicit central difference integration method.

In the FE model, the cable behaviour is more accurately modelled than in the analytical model, and perturbations from the ideal symmetric deployment can be investigated. The cables and tethers are modelled with a great number of cable elements, i.e. truss elements with a no-compression material. The main differences compared to the analytical model is that the cables can store elastic energy and that they are not constrained to be straight. Another important difference is that forces can be distributed in directions other than the radial. The simulated space web was coarser than the real space web, but the masses of the cables in the model are determined so that the total masses of the ideal and actual space webs are identical.

The coiling on and coiling off phenomena on the centre hub is important to model in the simulations. Therefore, the centre hub was modelled as a rigid body and not a point mass. The corner masses, however, can be modelled as point masses without loosing any important effects.

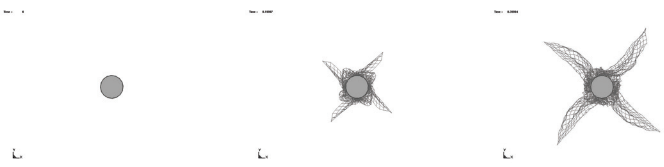
Contact phenomena will occur because of the large displacements. The contact between the cables and the rigid bodies, at the centre, was modelled using the kinematic constraint method.[11] This method enables coiling on of the space web without contact forces pushing the web away from the rigid bodies, as would be the case with the more common penalty method. If a cable node is within a small distance ϵ from a satellite surface, then the nodal displacements of the slave nodes (the cables) are transformed, on the global equations level, so that the degrees of freedom normal to the master surface (the centre hub) are eliminated. Impact and release conditions are then imposed to ensure conservation of momentum. The contact condition expires when the relative velocity becomes positive again.

Contact will also occur between the cables in the space web. Here, a node-to-surface variant of the penalty method is used. In the case of penetration, equal and opposite forces are applied. This implies a more elastic behaviour which is more realistic for the cable-to-cable contact.

Damping has not been included in this work. However, damping may be important, especially if it is used as part of the control strategy or to remove excessive energy. LS-DYNA has routines to deal with damping if this will be required at a later stage.

All the nodes are given initial rotations and initial velocities proportional to the distance from the centre of mass. Torque and external forces can also be applied during the deployment.

Finally, one of the main problems to solve is how to fold the membrane around the centre hub in the most realistic way. A folding pattern where the space web is perfectly folded around a circular hub is impossible to create, since the cables were modelled straight and



(a) t=0 s (b) t=0.2 (c) t=0.4

(d) t=0.6 (e) t=0.8 (f) t=1.0

Figure 1: Free deployment of space web.

with a certain length determined by the total computation cost. Also, to fold the cables near the centre hub is not even trivial in reality. Our solution to this problem was to move the nodes nearest, and inside, the centre hub to the periphery of the hub. Initial contacts between cable elements in the space web were disregarded, since higher priority was focused on coiling the space web as near the centre hub as possible in the initial state.

5 Results

Deployment of coiled star folded web

Quadratic space webs folded into the star pattern have been shown to be of certain interest. Several different deployment simulations of a large space web with side 100 m have been performed. The following data has been used in all the simulations: $S = 100\,\text{m}$, $m_h = 100$ kg, $r_0 = 6.3$ m, $\rho_A = 1.267 \cdot 10^{-2}$ kg/m^2, $m_c = 10$ kg, $E_{\text{ca}} = 180 \cdot 10^9$ Pa, $\rho_{\text{ca}} = 1540$

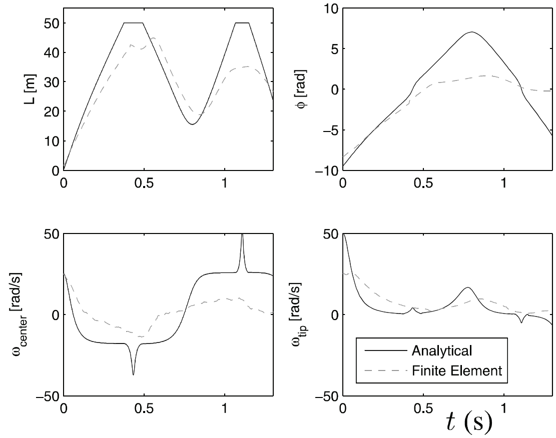


Figure 2: Free deployment of space web.

kg/m^3, $A_{\mathrm{ca}} = 2.5/0.030 \cdot 1.23 \cdot 10^{-7}$ m^2 and $t = 2.5$ m. E_{ca}, ρ_{ca}, A_{ca} are respectively the Elastic modulus, the density and the cross-sectional area of the cables in the model space web. Note that the area is adjusted so that the total weight of the model web becomes the same as for a real web with 0.030m mesh size. Where four graphs are shown, the graphs show the length of the deployed arm L, the angular deviation from the radial direction φ, the angular velocity of the inner hub ω_{centre} and the angular velocity of the tip of the arm ω_{tip}.

Free deployment of star arms

The free deployment of the star arms coiled around the centre hub was simulated, Figure 1 and 2. The deployment is initiated by an initial rotational velocity of 8π rad/s on the hub and the web. The star arms are coiled off from the hub, but then coiled on the centre hub again. The agreement between the two models is rather good for the length of the deployed arm, but not for the rotational velocities because the arms are not straight.

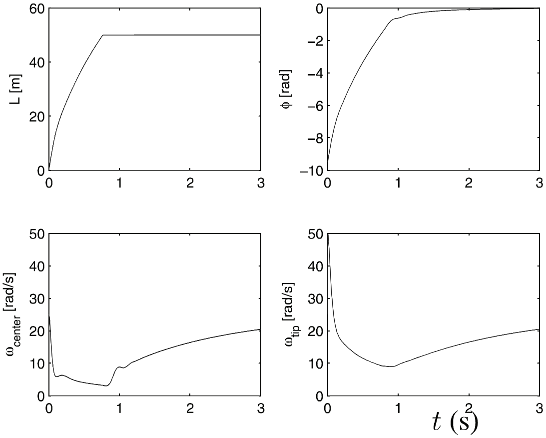


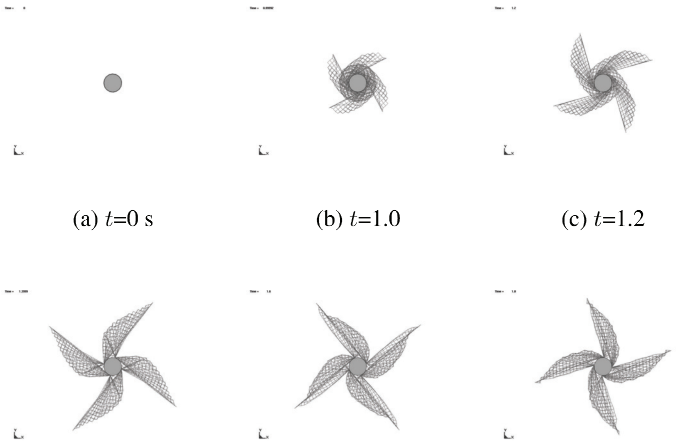
Figure 3: Deployment of space web using the control law in Eq. (1) with $M_0 = \omega_0 \cdot 10^5$.

Controlled deployment of star arms

An applied torque, again using Eq. (1), can be used to stabilise the deployment, see Figure 3. A torque that is feedback controlled in the FE model is necessary, which is described in section 3.

Rotational velocity according to Salama *et al.*

Salama *et al.*[10] propose linearly increasing angular velocity of the inner hub, from 0 at time $t = 0$ to ω_{max} at time $t = \Delta t$, and then keep the angular velocity constant at ω_{max}. There is no systematic way to choose these parameters, but using the values $\omega_{\text{max}} = 8\pi$ rad/s and $\Delta t = 2$ s as in the article by Salama *et al.*,[10] results in the deployment in Figure 4 and 5. The arms are coiled off the centre hub, and not coiled back on the hub again. However, there are undesired oscillations in the plane of rotation.



(a) t=0 s (b) t=1.0 (c) t=1.2

(d) t=1.4 (e) t=1.6 (f) t=1.8

Figure 4: Deployment of a space web with rotational velocity varying linearly from 0 at $t = 0$ to 8π rad/s at 2 s.

6 SOME CONCLUSIONS

- The analytical and the finite element models produce almost identical results when the arms are straight, i.e. when energy is transferred from the hub to the arms, and a stiff material is used, i.e. no elasticity is involved. When material data for Zylon is used, then the deployment is still similar, but different oscillatory behaviour occurs after the arms have been fully deployed.
- Both the analytical and finite element models show that free deployment, at least without damping, is not possible.
- To stabilise the deployment, a torque can be applied to the central hub.
- The most difficult modelling problem in LS-DYNA is how to coil the web near the hub and at the same time include contact between web members.

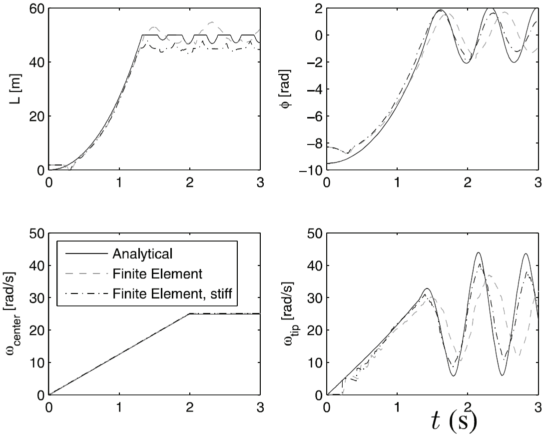


Figure 5: Deployment of a space web with rotational velocity varying linearly from 0 at $t = 0$ to 8π rad/s at 2 s.

- A user defined load can be applied in LS-DYNA to test the feedback control proposed by Melnikov and Koshelev.[8] However, this is not presented in this article.

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