АВТОМАТИЗИРОВАННЫЕ СИСТЕМЫ НАУЧНЫХ ИССЛЕДОВАНИЙ

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CONTROL OF SPACE TETHER SYSTEM DEPLOYMENT WITH ATMOSPHERIC PROBE

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Process of space tether system (STS) deployment control with atmospheric probe (AP) is analyzed in this paper. It is showed that establishing nominal deployment program of tether system with considering atmospheric drag decreases error of driving system to the given final state several times. Numerical simulation, analysis of results and conclusions in the form of formula are given.

Space tether system (STS) is composed of spacecraft, tether and atmospheric probe (AP). Atmospheric probe is a inflatable or folding structure, which has increasing ballistic coefficient. Atmospheric probe can be used, for example, to monitor the upper atmosphere.

A commonly used motion model in orbit moving coordinate system is utilized for establishing nominal deployment trajectory of STS at a position, which is near the vertical [1]

$$\ddot{L} = L[(\dot{\theta}+\dot{u})^2 - \dot{u}^2(1-3\cos^2\theta)] + \frac{Q_L - T_n}{M_e}, \tag{1}$$

$$\ddot{\theta} = -2\frac{\dot{L}}{L}(\dot{\theta}+\dot{u}) - \frac{3}{2}\dot{u}^2\sin 2\theta + \frac{Q_\theta}{M_e L^2}, \tag{2}$$

where L and θ are the tether length and tether deviation angle with the vertical, u is argument of latitude of center of mass orbit, $M_e = m_1 m_2 / M$, m_1 and m_2 are masses of spacecraft and probe, $M = m_1 + m_2$, T_n is tether tension force, Q_L and Q_θ are generalized atmospheric forces. In order to obtain (1-2) it is assumed that the orbit of system center of mass does not change, and is near a circular orbit during system deployment.

Program of STS deploying to the vertical position is expressed as

$$T_n = M_e\dot{u}^2[a(L-L_k) + b\dot{L}/\dot{u} + 3L_k], \tag{3}$$

where a,b are parameters of control law, L_k is final length of tether. If the orbit of center of mass is circular, then $\dot{u} = const$.

Generalized atmospheric forces are defined from expressions $Q_L = \delta A_L / \delta L$, $Q_\theta = \delta A_\theta / \delta\theta$, where δA_L and δA_θ are work of possible displacements δL, $\delta\theta$.

Therefore

$$Q_{\theta 1} = -C_1 S_1 \rho_1 V_{r1} \cdot \Delta L_1 \cdot (V_{o1}\cdot\cos(\theta-\varphi_1) + V_{\theta 1}) / 2 \tag{4}$$

$$Q_{L1} = -C_1 S_1 \rho_1 V_{r1} \cdot m_2 \cdot (V_{o1}\cdot\sin(\theta-\varphi_1) + V_{L1}) / 2M \tag{5}$$

$$Q_{\theta 2} = C_2 S_2 \rho_2 V_{r2} \cdot \Delta L_2 \cdot (V_{o2}\cdot\cos(\theta+\varphi_2) - V_{\theta 2}) / 2 \tag{6}$$

$$Q_{L2} = C_2 S_2 \rho_2 V_{r2} \cdot m_1 \cdot (V_{o2}\cdot\sin(\theta+\varphi_2) - V_{L2}) / 2M \tag{7}$$

where $C_{1,2}$ are coefficients of atmospheric drag, $S_{1,2}$ are cross-sectional areas, $\rho_{1,2}$ are atmospheric density, $\Delta L_{1,2} = m_{2,1}L/M$, angles $\varphi_{1,2}$ and components $V_{o1,2}$, $V_{L1,2}$, $V_{\theta 1,2}$ sum of velocities $V_{r1,2}$ spacecraft and probe are defined according to Fig.1.

Generalized forces, which are in system (1-2) are defined as sum of expressions (4-7): $Q_\theta = Q_{\theta 1} + Q_{\theta 2}$, $Q_L = Q_{L1} + Q_{L2}$.

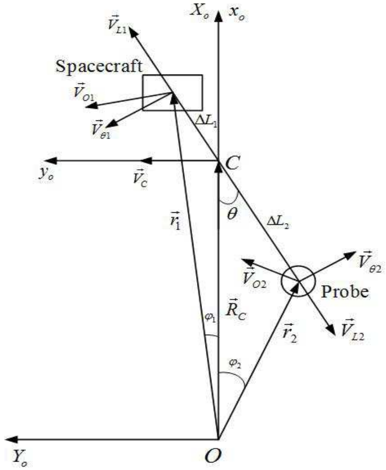

Fig. 1. Positions of spacecraft and probe with respect to orbit coordinate system

Motion equations of STS in geocentric coordinate system are expressed in the following form [1]

$$\frac{d\vec{r}_k}{dt} = \vec{V}_k, \quad m_k\frac{d\vec{V}_k}{dt} = \vec{G}_k + \vec{T}_k + \vec{R}_k \tag{8}$$

where $\vec{r}_k$ ($k = 1,2$) are radius vectors of spacecraft and probe, $\vec{V}_k$ are absolute velocities of end-bodies, $\vec{G}_k, \vec{T}_k, \vec{R}_k$ are vectors of gravity, tether tension force and atmospheric drag.

Because tether does not sustain compressive force, tether tension is calculated according to Hooke's law

$$T=\begin{cases} c\dfrac{|\vec r_1-\vec r_2|-l}{L}, & if \quad |\vec r_1-\vec r_2|-l\ge 0 \\ 0, & if \quad |\vec r_1-\vec r_2|-l\le 0 \end{cases} \tag{9}$$

where l is the length of undeformed tether, $c=E\cdot A$ is stiffness coefficient, E is Young's modulus, A is the cross sectional area of tether.

According to the vector form tether tension force is defined in the form of vectors

$$\vec T_1 = T\frac{\vec r_2-\vec r_1}{|\vec r_1-\vec r_2|},\ \vec T_2=-\vec T_1, \tag{10}$$

In order to establish deployment model of system (8), it is necessary to add equations, which account for dynamics of control mechanism performance. These equations are expressed as [2]

$$m_e\frac{dV_l}{dt}=T_1-F_c,\ \frac{dl}{dt}=V_l, \tag{11}$$

where coefficient m_e accounts for inertia of the control mechanism, V_l is tether velocity, F_c is the control force of tether deployment mechanism.

According to the principle of feedback force, F_c is given as [2,3]

$$F_c=T_n+p_1\Delta L+p_2\Delta V, \tag{12}$$

where p_1, p_2 are control coefficients, T_n is nominal tether tension force (3), $\Delta L=l-L$, $\Delta V=V_l-V_L$.

Fig. 2-3 show trajectories of probe with respect to spacecraft, which nominal trajectories are showed in dashed lines and perturbed trajectories are showed in solid lines. Analysis of the results shows that utilizing nominal deployment program without considering atmospheric drag (Fig.2) leads to large error in the end of deployment, and the probe vibrates with respect to the vertical. Utilizing nominal deployment program with considering atmospheric drag decreases control error. From the comparison of Fig.2-3 it is showed that control error decreases about 36 times.

Parameters of numerical simulation are selected as: $m_e=0.2kg$, $m_1=6000kg$, $m_2=20kg$, $L_k=30km$, $a=4, b=5$, ballistic coefficients $\sigma_1=1.257\cdot10^{-3}m^2/kg$, $\sigma_2=0.015m^2/kg$; coefficients of control $p_1=0.243$, $p_2=7.824$ [4].

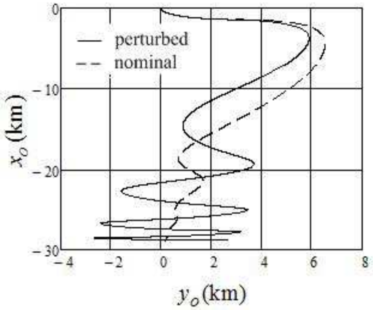

Fig. 2

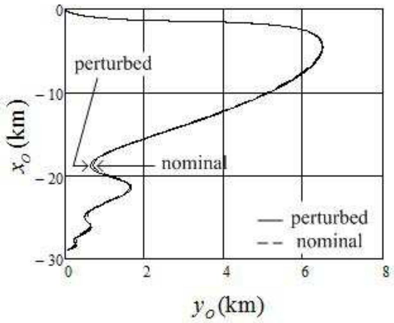

Fig. 3

In this way, utilizing nominal deployment program without considering atmospheric drag leads to large error in the end of deployment, and the probe vibrates with respect to the vertical. Utilizing nominal deployment program with considering atmospheric drag decreases control error. These conclusions remain valid when inclination of the STS center of mass orbit and atmosphere rotation are concerned.

References

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