Proceeding of the IEEE
International Conference on Robotics and Biomimetics
Dali, China, December 2019

Spin-up Control of Tethered Space Station for Artificial Gravity Task *

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***Abstract* - In order to overcome the problems caused by the zero gravity of space, artificial gravity space station has been widely concerned in recent years. The tether-based space station relies on the centrifugal force generated by its rotation around the centroid to simulate gravity, which greatly reduces various problems caused by the zero gravity environment, and has many advantages such as low spin speed, flexibility, and scalability. For the spin-up process of the tethered space station, a dynamic model of the tethered space station based on the Lagrange method is established firstly. Then, the control law using sliding mode theory and the dynamic inversion is proposed. Different spin-up schemes are designed to test the control law. Simulation results shows that whether the system's tether retraction rate is adjustable or not, the angular velocity of the system can smoothly reach the desired value to produce the expected level of artificial gravity.**

Index Terms* - *Tethered space station, Artificial gravity, Sliding mode control

I. INTRODUCTION

The space station is an valuable scientific experimental platform and military base. With the development of space industry, it plays an increasingly important role in international competition. The current space station is in a zero-gravity environment, which transforms the astronauts' body with many undesirable effects such as muscle loss, immunity decrease, biological rhythm disorders, visual impairment and so on [1,2]. When astronauts return to Earth, they also need to re-adapt to the earth's gravity environment [3]. This will not only affect the working capacity of the station staff, but will also hinder the future manned exploration of Mars, asteroids and other long-term deep space exploration missions. Therefore, it makes sense to build a controlled artificial gravity environment at the space station.

At present, the idea of an artificial gravity space station is a pure rigid body structure. The space station rotates rapidly around its center of mass and relies on the centrifugal force generated by the spin to simulate gravity. However, the construction of a pure rigid body structure is difficult, and the overall size is strictly limited. It is difficult to build a system with a diameter of more than 100 meters, which requires a high spin speed to generate gravity. Such a large angular velocity will create the distinct gradient of centrifugal force, which also has negative impact on human health, so it is not suitable for application [4].

At the end of the 19th century, Tsiolkovski, the pioneer of manned space flight, proposed the idea of using a tether to connect two spacecraft rotating around its center of mass of the system to generate centrifugal force and simulate artificial gravity. In recent years, Yanhua Han verified through simulation that the reasonable selection of tether length and spin angular velocity can produce artificial gravity suitable for astronauts [5]. Kaela M. Martin proposes a maneuver that is performed while the spacecraft is spinning thus avoiding additional spin-down and spin-up maneuvers [6]. Xingwang Gou gives an artificial gravity stabilization method based on overload feedback for high eccentricity transfer orbits [7]. However, there is currently no direct research on the tethered artificial gravity space station. The research related to the tether system focuses on tethered satellite, tethered satellite formation and tethered space robot. Many of the research on dynamics and control of tether system can provide reference for the study of tethered space station [8].

On the basis of the dumbbell configuration, the control capsule is introduced into the center of the tether system. The spacecraft at both ends (crew capsule) rotate around the centroid of the control capsule to maintain the tension of the tether, thus producing artificial gravity as shown in Fig. 1. Such structure not only reduces various problems brought by zero-gravity environment, but also has many advantages such as low spin speed, flexibility and scalability.

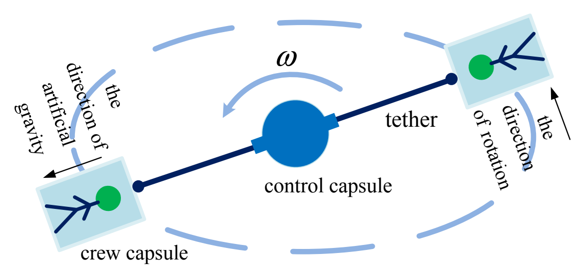

Fig. 1 Illustration of artificial gravity generated by tethered space station

* This work is partially supported by the National Natural Science Foundation of China (Grant No: 61773317), Natural Science Basic Research Plan in Shaanxi Province of China (Program No: 2019JM-406) and the Fundamental Research Funds for the Central Universities (Grant No: 3102018JGC001).

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This paper studies the spin-up method of the tethered space station. It is organized as follows. In section II, a dynamic model of tether space station based on Lagrange method is proposed. Section III designs the spin-up control law based on sliding mode control. Section IV tests the performance of the controller through simulation and discusses the simulation results. The conclusions and further work are presented in the final section.

II. Model Formulation

As shown in Fig. 2, the space station is centered on the control capsule, and two ends of the equal-length tether are respectively connected to two equal-mass crew capsules. The control capsule is mainly responsible for transfer maneuvers, release and recycle of the tether. The crew capsules are mainly responsible for generating artificial gravity environment and adjusting the spin speed and attitude of the system. Therefore, the control capsule only needs to adjust its own speed to match the overall spin of the tethered space station, and does not need to drive the system spin. Since the tether is quite long, the effect of the end body on the tether is not significant [9], so both the control capsule and the crew compartment can be considered as mass points. Then several assumptions are employed as follows.

(1) The space station control capsule and the two passenger capsules are considered as mass points. Their attitude are ignored.

(2) The connected tether is regarded as a rigid rod that does not deform, ignoring its elasticity and flexibility [10, 11].

(3) The system center of mass is always in the orbital plane [12].

(4) Orbit Perturbation is temporarily ignored [10]. The external force of the system is only the gravity of the earth and the thrusts.

The dumbbell-like structure and coordinate of tethered space station is shown in Fig. 2. The earth centered inertial coordinate frame $Oxyz$ is used to provide inertial reference. The attitude of the space station is described by its Euler angle with respect to the orbital coordinate frame $Ox_oy_oz_o$. Given ρ is the linear density of the tether, $m_t=\rho l_1=\rho l_2$ is the tether mass. $m_1=m_2=m_c$ is crew capsule mass. The total mass of the system is $m=m_s+2m_c+2m_t$. During the spin-up period, the motion of the system is symmetrical according to the assumption. Set $2l=l_1+l_2$, then we can use l to measure the telescopic movement of the system. There are five degrees of freedom in the system: centroid vector diameter $\boldsymbol{r}$, the true anomaly f, In-plane pitch angle θ, out-of-plane roll angle φ and tether length l, where $\boldsymbol{r}$ f are used to describe the motion of the system centroid in the orbital plane, θ φ l are used to describe the attitude motion. Based on the model proposed by Williams [10], the dynamic model of the system will be derived next.

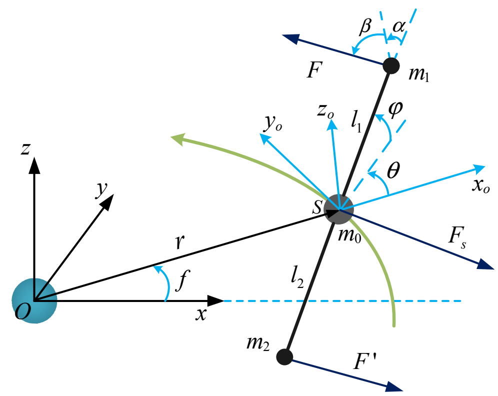

Fig. 2 System configuration of tether space station

By ignoring the elasticity and flexibility of the tether, the system consisting of the control capsule, the crew capsule and the tether can be considered as rigid body to analyze system orbital and attitude motion. The total kinetic energy of the tethered space station T_{tot} can be regarded as the sum of the kinetic energy of the system centroid, the rotational kinetic energy around the centroid and the telescopic kinetic energy with respect to mass center:

$$\begin{aligned} T_{tot} &= \frac{1}{2}m(\dot{r}^2+\dot{f}^2r^2)+(m_t+m_c)\dot{l}^2 \\ &+(m_c+\frac{1}{3}m_t)l^2\left[\dot{\varphi}^2+(\dot{f}+\dot{\theta})^2\cos^2\varphi\right] \end{aligned} \tag{1}$$

The potential energy of the tethered space station is approximated by the sum of potential energy of each capsule:

$$W=-\frac{\mu m}{r}-\frac{\mu m_c l^2}{r^3}\left(3\cos^2\theta\cos^2\varphi-1\right) \tag{2}$$

Use Lagrange method to deduce the dynamic model of tethered space station:

$$\frac{d}{dt}(\frac{\partial L}{\partial \dot{q}_j})-\frac{\partial L}{\partial q_j}=Q_j \tag{3}$$

where q_j and Q_j are the generalized coordinates of the degrees of freedom and non-conservative generalized external forces, respectively. L is the Lagrange function:

$$\begin{aligned} L=T_{tot}-W &= \frac{1}{2}m(\dot{r}^2+\dot{f}^2r^2)++(m_c+m_t)\dot{l}^2 \\ &(m_c+\frac{1}{3}m_t)l^2\left[\dot{\varphi}^2+(\dot{f}+\dot{\theta})^2\cos^2\varphi\right] \\ &+\frac{\mu m}{r}+\frac{\mu m_c l^2}{r^3}\left(3\cos^2\theta\cos^2\varphi-1\right) \end{aligned} \tag{4}$$

The dynamic model for the tethered space station is achieved as follows:

$$
\begin{cases}
\ddot{r} = \dot{f}^2 r - \dfrac{\mu}{r^2} - \dfrac{3\mu m_c l^2}{m r^4}\left(3\cos^2\theta\cos^2\varphi - 1\right) + \dfrac{Q_r}{m} \\
\ddot{f} = \dfrac{-2mr\dot{r}\dot{f} - 2(m_\mathrm{c} + \frac{1}{3}m_\mathrm{t})l^2\left[\ddot{\theta}\cos^2\varphi - \sin 2\varphi\dot{\varphi}(\dot{f}+\dot{\theta})\right]}{mr^2 + 2(m_\mathrm{c} + \frac{1}{3}m_\mathrm{t})l^2\cos^2\varphi} \\
\quad - \dfrac{2(2m_\mathrm{c} + m_\mathrm{t})l\dot{l}\left(\dot{f}+\dot{\theta}\right)\cos^2\varphi - Q_f}{mr^2 + 2(m_\mathrm{c} + \frac{1}{3}m_\mathrm{t})l^2\cos^2\varphi} \\
\ddot{\theta} = (\dot{f}+\dot{\theta})\left[2\tan\varphi\dot{\varphi} - \dfrac{(2m_\mathrm{c}+m_t)\dot{l}}{(m_\mathrm{c}+\frac{1}{3}m_t)l}\right] - \ddot{f} - \dfrac{3\mu m_c \sin 2\theta}{2(m_\mathrm{c}+\frac{1}{3}m_\mathrm{t})r^3} \\
\quad + \dfrac{Q_\theta}{2(m_\mathrm{c}+\frac{1}{3}m_\mathrm{t})l^2\cos^2\varphi} \\
\ddot{\varphi} = -\dfrac{2m_\mathrm{c}+m_t}{m_\mathrm{c}+\frac{1}{3}m_t}\dfrac{\dot{l}}{l}\dot{\varphi} - \left(\dot{f}+\dot{\theta}\right)^2\cos\varphi\sin\varphi \\
\quad - \dfrac{3\mu m_c\cos^2\theta\sin 2\varphi}{2(m_\mathrm{c}+\frac{1}{3}m_t)r^3} + \dfrac{Q_\varphi}{2(m_\mathrm{c}+\frac{1}{3}m_t)l^2} \\
\ddot{l} = \dfrac{-m_t}{m_c+m_t}\dfrac{\dot{l}^2}{l} + \dfrac{m_\mathrm{c}+\frac{1}{3}m_t}{m_c+m_t}l\left[\dot{\varphi}^2 + (\dot{f}+\dot{\theta})^2\cos^2\varphi\right] \\
\quad + \dfrac{\mu m_c l}{(m_c+m_t)r^3}\left(3\cos^2\theta\cos^2\varphi - 1\right) + \dfrac{Q_t}{m_c+m_t}
\end{cases}
\tag{5}
$$

Then the system has four-degree-of-freedom motion. When no external force is input, the dynamic model can be transformed into stable spin state to generate artificial gravity. In an artificial gravity environment, the centripetal acceleration that astronauts stand is equal to the magnitude of the overload they receive, and is equal to the acceleration generated by tension on the crew capsule. In this period, the tether is fully extended, so the length of the tether is no longer changed. It can be considered that $\dot{l} = \ddot{l} = 0$. So the tether tension can be obtained according to (5):

$$
\begin{aligned}
T = {} & (m_\mathrm{c} + \frac{1}{3}m_t)l\left[\dot{\varphi}^2 + (\dot{f}+\dot{\theta})^2\cos^2\varphi\right] \\
& + \frac{\mu m_c l}{r^3}\left(3\cos^2\theta\cos^2\varphi - 1\right)
\end{aligned}
\tag{6}
$$

When the crew capsule acceleration a is equal to the earth's surface gravity acceleration g_0, the overload that astronauts are subjected to is equal to the gravity on the ground, thus the simulation of gravity is achieved. Ignore the period terms and the required in-plane angular velocity can be calculated as:

$$
\dot{\theta}_0 = \pm\sqrt{\frac{g_0(3m_c + m_t) - 3m_c l\dot{\varphi}_0^2}{3m_c l\cos^2\varphi_0}} - \dot{f}_0 \tag{7}
$$

III. Control Strategy Design

By adjusting the tether length and spin angular velocity to a specific value, a stable artificial gravity environment can be provided [5]. So the adjustment of the tether length and the angular velocity become the core of the control task. In addition, we choose to spin in the orbital plane to reduce the coupling between the in-plane pitch and the out-of-plane roll channel, so it is necessary to suppress the initial disturbance of the out-of-plane roll angle and keep it at the equilibrium position.

System state equation

As shown in Fig. 2, thrust F and F' constitute the force couple acting on the two crew capsules. α and β are the direction angles with respect to the space station. The expressions of the generalized forces in (5) are as follows:

$$
\begin{cases}
Q_r = F_r, Q_f = F_f r,\ \ Q_\theta = Fl\sin\alpha\cos\beta, \\
Q_\varphi = Fl\sin\beta,\ \ Q_t = F\cos\alpha\cos\beta
\end{cases}
\tag{8}
$$

Let $x_1 = l, x_2 = \dot{l}, x_3 = \theta, x_4 = \dot{\theta}, x_5 = \varphi, x_6 = \dot{\varphi}$, the attitude dynamic equation of the tethered space station can be written as:

$$
\begin{cases}
\dot{x}_1 = x_2 \\
\dot{x}_2 = b_1 + d_1 F_t \\
\dot{x}_3 = x_4 \\
\dot{x}_4 = b_2 + d_2 F_\theta \\
\dot{x}_5 = x_6 \\
\dot{x}_6 = b_3 + d_3 F_\varphi
\end{cases}
\tag{9}
$$

where $F_t = F\cos\alpha\cos\beta, F_\theta = F\sin\alpha\cos\beta,\ F_\varphi = F\sin\beta$ are the control force components of thrust F acting on each state variable. The other expressions are determined by (5).

Hierarchical sliding mode controller

When the tether retraction rate is not adjustable, the length of the tether and angular velocity should be adjusted by thrust. It is necessary to design the controller so that the tether length and the angular velocity respectively tend to the desired value. For feedback control, define the deviation between the expected value and the state variable as follows:

$$
\begin{cases}
e_1 = l_d - x_1\ ,\ \ de_1 = \dot{l}_d - x_2 \\
e_2 = \theta_d - x_3\ ,\ \ de_2 = \dot{\theta}_d - x_4
\end{cases}
\tag{10}
$$

where e_1 and de_1 are the state error of the tether length and its change rate. e_2 and de_2 are the error of the in-plane angle and its velocity. $\dot{l}_d$ can be obtained by taking the derivative of l_d with respect to time, θ_d can be obtained by integrating $\dot{\theta}_d$ with respect to time. According to the number of constraints, 5 high-order polynomials are used to interpolate l_d :

$$l_d(t) = a_0 + a_1(t-t_0) + a_2(t-t_0)^2 + a_3(t-t_0)^3 + a_4(t-t_0)^4 + a_5(t-t_0)^5 \tag{11}$$

Linear function is adopted to plan $\dot{\theta}_d$:

$$\dot{\theta}_d(t) = \dot{\theta}_0 + k(t-t_0),\quad k = \frac{\dot{\theta}_f - \dot{\theta}_0}{t_f - t_0} \tag{12}$$

In (9), (x_1 , x_2) and (x_3 , x_4) can be regarded as two subsystems, and their corresponding sliding mode surfaces s_1 and s_2 are defined as follows:

$$\begin{cases} s_1 = c_1(l_d - x_1) + (\dot{l}_d - x_2) \\ s_2 = c_2(\theta_d - x_3) + (\dot{\theta}_d - x_4) \end{cases} \tag{13}$$

where c_1 and c_2 are the coefficients to be adjusted.

Let $\dot{s}_1 = \dot{s}_2 = 0$, the equivation control law can be derived according to the Filippov theory:

$$\begin{cases} F_t' = \dfrac{c_1(\dot{l}_d - x_2) + \ddot{l}_d - b_1}{d_1} \\ F_\theta' = \dfrac{c_2(\dot{\theta}_d - x_4) + \ddot{\theta}_d - b_2}{d_2} \end{cases} \tag{14}$$

Define the total sliding surface of the system as a linear combination of the sliding surfaces of the two subsystems: $s = as_1 + bs_2$, where a and b are weighing coefficients.

Let the system move towards the sliding surface, then the derivative of total sliding surface of the system satisfies $\dot{s} = a\dot{s}_1 + b\dot{s}_2 = -\sigma s - \varepsilon\,\mathrm{sat}(s)$. The pseudo-inverse method is used to obtain the switching law of l and θ channels:

$$\begin{cases} F_t'' = \dfrac{ad_1(-\sigma s - \varepsilon\,\mathrm{sat}(s))}{a^2 d_1^2 + b^2 d_2^2} \\ F_\theta'' = \dfrac{bd_2(-\sigma s - \varepsilon\,\mathrm{sat}(s))}{a^2 d_1^2 + b^2 d_2^2} \end{cases} \tag{15}$$

where σ and ε are designed constants, sats() is saturation function used to alleviate possible chattering.

$$\mathrm{sat}(s) = \begin{cases} 1 & s > \Delta \\ s/\Delta & -\Delta < s < \Delta \\ -1 & s < \Delta \end{cases}$$

where Δ is a designed small positive constant.

The sliding mode control law consists of the switching control law that makes the system tend to the sliding surface and the equivalent control law of the motion on the sliding surface. Thus the total sliding mode control law of the system is:

$$\begin{bmatrix} F_t \\ F_\theta \end{bmatrix} = \begin{bmatrix} F_t' + F_t'' \\ F_\theta' + F_\theta'' \end{bmatrix} \tag{16}$$

Define Lyapunov function $V = \frac{1}{2}s^2$, take its derivative:

$$\begin{aligned} \dot{V} &= s\dot{s} \\ &= s(a\dot{s}_1 + b\dot{s}_2) \\ &= s\{a[c_1(\dot{l}_d - x_2) + \ddot{l}_d - b_1 - d_1(F_t' + F_t'')] \\ &\quad + b[c_2(\dot{\theta}_d - x_4) + \ddot{\theta}_d - b_2 - d_2(F_\theta' + F_\theta'')]\} \end{aligned}$$

Substitute (16) into it:

$$\begin{aligned} \dot{V} &= -\sigma s^2 - \varepsilon s \cdot \mathrm{sat}(s) \\ &= -\sigma s^2 - \varepsilon |s| \le 0 \end{aligned}$$

According to the Lyapunov stability theory, the system will move along the sliding surface to the desired equilibrium position under the control law.

Dynamic inverse controller

For the out-of-plane angular disturbance, the state variables of the rolling channel can be divided into two layers, the outer layer is indirectly controlled, and the inner layer is directly controlled. The change rate of state from the inside to the outside is reduced, so that the controller can be designed to stabilize the out-of-plane angle layer by layer in two loops.

In (9), $\dot{\varphi}$ is written as a pseudo-linear form : $x_6 = b_3 + d_3 F_\varphi$. Define the state error de_3 as $de_3 = \dot{\varphi}_d - x_6$, where $\dot{\varphi}_d$ is the desired out-of-plane angular velocity, and the purpose of the control is to let the error be zero. Due to reversibility of d_3 , the control law of out-of-plane angular velocity is:

$$F_\varphi = d_3^{-1}(-b_3 + k_d de_3) \tag{17}$$

where the out-of-plane angular acceleration satisfies $\dot{x}_5 = x_6$. Rewrite it as a pseudo-linear form: $\dot{x}_5 = b_4 + d_4 x_6$, where $b_4 = 0$, $d_4 = 1$. The equation lack control variable. If the expected out-of-plane angular velocity $\dot{\varphi}_d$ is set to the virtual control variable, in order for x_5 to track φ_d , there is:

$$\dot{\varphi}_d = d_4^{-1}(-b_4 + k_p e_3) \tag{18}$$

where $e_3 = \varphi_d - x_5$ is the deviation of the out-of-plane angle. In order to make the system spin in the orbital plane, it is desirable that the out-of-plane angle φ_d should be equal to the equilibrium outer angle $\varphi_e = 0$. Since the expected command of the inner loop is the output of the outer loop, substitute (18) into (17) and the out-of-plane angle control law is obtained:

$$F_{\varphi}=d_3^{-1}\{-b_3+k_d[d_4^{-1}(-b_4+k_p e_3)-x_6]\} \tag{19}$$

The complete control scheme is shown in Fig. 3 and the control law of the entire system is as follows:

$$\begin{cases} F_t=\dfrac{c_1(\dot{l}_d-x_2)+\ddot{l}_d-b_1}{d_1}+\dfrac{ad_1(-\sigma s-\varepsilon\,\mathrm{sat}(s))}{a^2d_1^2+b^2d_2^2} \\ F_\theta=\dfrac{c_2(\dot{\theta}_d-x_4)+\ddot{\theta}_d-b_2}{d_2}+\dfrac{bd_2(-\sigma s-\varepsilon\,\mathrm{sat}(s))}{a^2d_1^2+b^2d_2^2} \\ F_{\varphi}=d_3^{-1}\{-b_3+k_d[d_4^{-1}(-b_4+k_p e_3)-x_6]\} \end{cases} \tag{20}$$

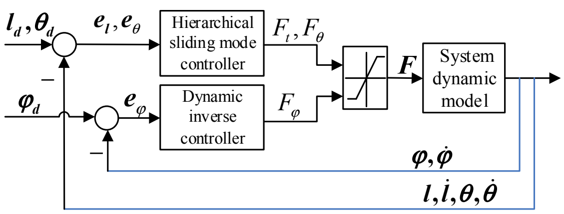

Fig. 3 The complete spin-up control scheme

IV. Simulation Results

The spin-up maneuver can be divided into two processes: releasing the tether and spinning up. If they are performed simultaneously, the reel mechanism will overcome a large amount of centrifugal force during the release process, because the expected angular velocity is relatively high. Considering the actual situation does not always meet the requirements, so the spin-up maneuver in both cases is discussed separately. If the reel mechanism cannot overcome the centrifugal force, the retraction rate of the tether is not adjustable. When the tether reaches the expected length, the space station begin to spin up after the tether is fixed .If the reel mechanism can overcome the centrifugal force to adjust the tether retraction rate, the tether release rate can be planned, and lateral thruster can then be used to control the spin angular velocity, so that the overload tends to the expected value as quickly as possible. Select the Low earth circular orbit for simulation, the system parameters are listed in Table I.

TABLE I
Initial Values And Controller Parameters

Parameters	Values	Parameters	Values
ρ	$0.3\mathrm{kg}/m$	m_c	10t
$(r\ \ \dot{r})$	(6871km 0m/s)	m_0	17t
$(f\ \ \dot{f})$	$(0^\circ\ \ 0.0635^\circ/\mathrm{s})$	$(c_1\ \ c_2)$	(0.3 0.5)
$(\theta\ \ \dot{\theta})$	$(-1^\circ\ \ 0.001^\circ/\mathrm{s})$	$(a\ \ b)$	(1 1)
$(\varphi\ \ \dot{\varphi})$	$(2^\circ\ \ 0.002^\circ/\mathrm{s})$	$(\sigma\ \ \varepsilon)$	(0.07 0.02)
$(l\ \ \dot{l})$	(10m 0m/s)	$(k_p\ \ k_d)$	(0.02 0.08)

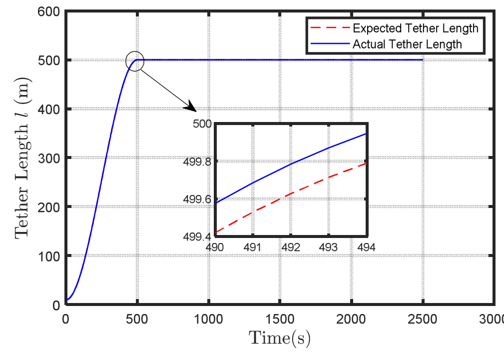

Fig. 4 Length of the tether

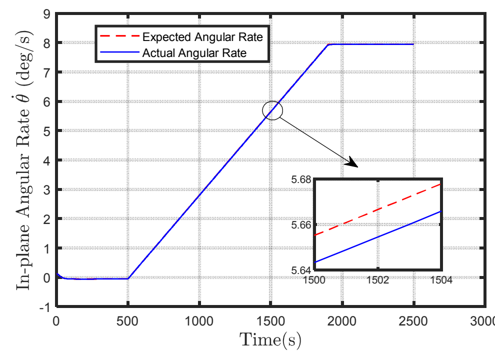

Fig. 5 In-plane angular rate

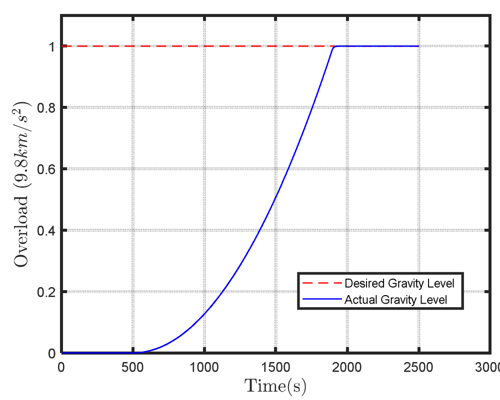

Fig. 6 The overload of the crew capsule

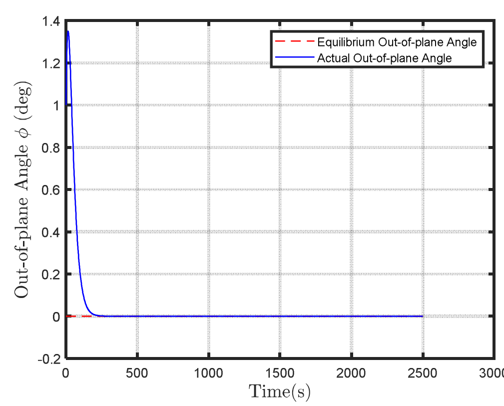

Fig. 7 Out-of-plane angle

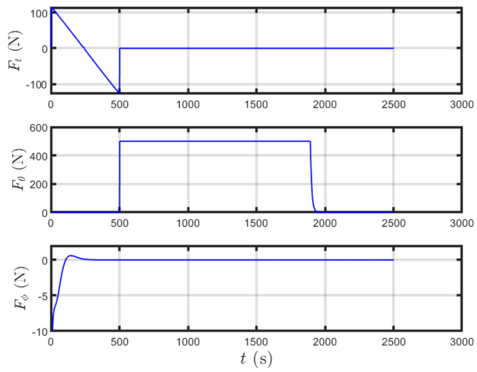

Fig. 8 Thrust of three directions

For the first case, if the tether retraction rate is not adjustable, during the tether release process, there is no tension on the tether. When the system starts to spin, the tension is gradually increased. The two processes can be performed sequentially by adjusting the controller parameters, and the out-of-plane angle should be stabilized at the same time, Simulation results shown in Fig. 4-8.

From Fig. 4-6, the tether length and in-plane angular rate of the space station can track curves we planned smoothly, with a good tracking effect, and finally stabilize at the expected level. The overload remains substantially at zero during the release of the tether because the tether is free to release and there is no tension on the tether before it is fixed. As the system starts to spin, the level of the overload rises smoothly with the increase of the in-plane angular rate, and finally stabilizes near g_0.

Fig. 7 shows the curve of the out-plane angle. Under the action of the out-of-plane angular stability controller we designed, the out-plane angle quickly converges to the equilibrium position and no longer changes. In the subsequent control process, there will be no coupling effect with other channels.

Fig. 8 shows the curve of control force acting on each channel. The radial thrust is approximately linearly changed during the release of the tether. The tangential thrust is kept constant at around 500N during operation. The axial thrust is only less than 10N, and tends to 0 quickly. Therefore, a fixed-size thruster can be installed in the tangential direction of the crew capsule, and variable thrusters need to be installed in the other two directions.

When the tether retraction rate is adjustable, the space station is required to have a certain initial angular rate to maintain the tether tension, and then the tether can be released according to the planned curve through the reel mechanism. The artificial gravity station can be accelerated to reach the desired artificial gravity level, the initial angular rate is determined by (7). Then release the tether and slowly spin up the space station, during which the control objective is to keep the gravity as stable as possible.

According to the previous simulation, the out-of-plane angle can be quickly stabilized to the equilibrium position: $\varphi=\dot\varphi=0$. Since $m_t \ll m_c$, $l \ll r$, ignore the periodic disturbance and the overload expression of the astronaut obtained by (6) is:

$$n=\frac{(\dot f+\dot\theta)^2 l}{g_0} \tag{21}$$

Use equation (11) to plan $l(t)$. If the overload is to be stable at g_0 level, the expected in-plane angular rate is:

$$\dot\theta_d(t)=\sqrt{\frac{g_0}{l(t)}}-\dot f \tag{22}$$

Take the derivative of (21) and get the expected acceleration rate of in-plane Angle:

$$\ddot\theta_d(t)=\frac{-(\dot f+\dot\theta)\dot l(t)}{2\cdot l(t)}-\ddot f \tag{23}$$

Substitute the expected value into the control law, then the spin-up maneuver simulation results is shown in Fig. 9-11:

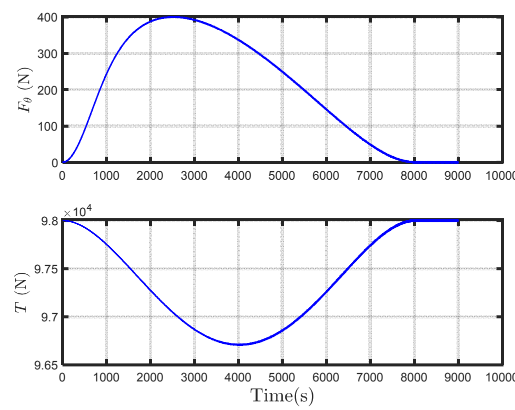

Fig. 9 The tangential thrust and tether tension

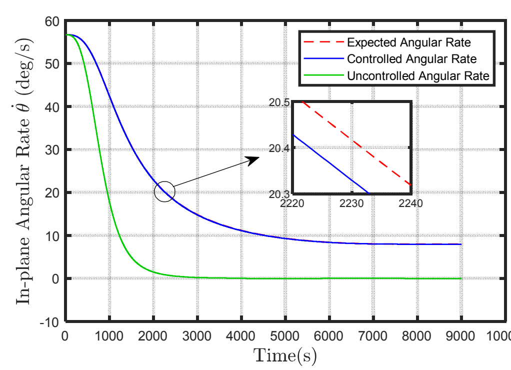

Fig. 10 In-plane angular rate

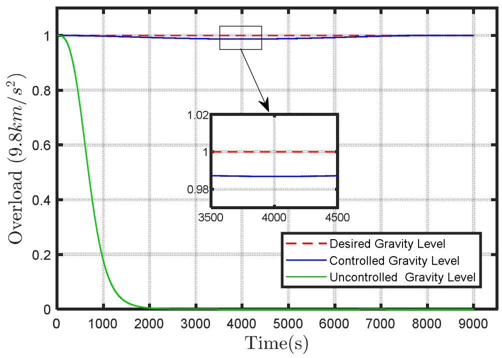

Fig. 11 The overload of the crew capsule

As shown in Fig. 9, the tangential thrust increases first and then decreases, and the curve is smooth. When the tether is released, it remains at the zero position. It can be deduced that if the gravity level is to be stabilized, the thrust force needs to be continuously variable. The tether tension first becomes smaller, then becomes larger, and finally coincides with the initial. During the whole process, the range of tether tension varies little, so the overload level also varies little.

Fig. 10 and 11 compare the curves of the spin angular rate and overload in the controlled and uncontrolled states respectively. When the tether is released uncontrolled, the system overload and the in-plane angular rate will rapidly decrease and tend to zero. This is because the angular momentum of the system is conserved. Under controlled of tangential thrust, the in-plane angular rate slowly decreases and eventually reaches a certain value. The level of overload remains essentially constant, with only a small range of floats, and eventually stabilizes at the desired level.

V. CONCLUSIONS AND FUTURE WORK

In this paper, the spin-up control problem of the tether space station is studied for artificial gravity task. The Lagrange method is used to derive the dynamic model of the tether space station based on the dumbbell configuration. The thrust control law of the spinning process is designed by means of hierarchical sliding mode. Dynamic inverse method is used to design the stability control law of out-plane angle. The simulation is verified for different spin-up schemes. For the case that the tether retraction rate is not adjustable, the results show that the controller can make the tether length and spin rate approach the expected value and get the desired overload smoothly. If the tether retraction rate is adjustable, the controller can stabilize the artificial gravity near g_0 level.

To simplify the model， this paper introduces some assumptions: The attitude of the control capsule of the tether space station is neglected. The elastic deformation of the tether is not considered. In the future, the dynamics model and spin control strategy of the system under more general conditions need to be further studied.

ACKNOWLEDGMENT

This work is supported by the National Natural Science Foundation of China (Grant No: 61773317), Natural Science Basic Research Plan in Shaanxi Province of China (Program No: 2019JM-406) and the Fundamental Research Funds for the Central Universities (Grant No: 3102018JGC001).

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