On Dependence of Equilibrium Characteristics of the Space Tethered System on Environmental Parameters

A.A. Tikhonov[1,2] and A.B. Yakovlev[1]
[1]Saint Petersburg State University, 7-9 Universitetskaya nab., Saint Petersburg, 199034, Russia
[2]Saint Petersburg Mining University, 2, 21st Line, Saint Petersburg, 199106, Russia

Abstract - The paper addresses the problem of attitude stabilization of electrodynamic space tether system (EDTS) in the local vertical position. The EDTS includes a negatively charged collector at the lower end of the tether and a positively charged collector at the upper end. The magnitude of the negative charge is under control. The Lorentz torque acting on the EDTS due to charged collectors at the ends of the tether significantly expands the stability area for the vertical position of the tether. The interaction of charged collectors with near-Earth plasma is analyzed. The results showed that during the continuous operation of the electron gun, the locally equilibrium values of the potentials of the collectors and charges on them can vary by a factor of 2-3, and the values of the currents in the tether and in the electron gun can vary by more than one order of magnitude.

Keywords - Electrodynamic tether, attitude stabilization, geomagnetic field, Lorentz torque, space plasma

I. INTRODUCTION

Consider a conductive tether deployed from a space system and orbiting the Earth. An electromotive force within the tether arises as it moves through the geomagnetic field. If either end of the tether is electrically in contact with the ionosphere plasma, an electric current will be able to flow through the tether by closing the circuit via the surrounding near-Earth plasma. If, in addition, plasma contactors at either end of the tether emit and collect electrons, a significant current in the tether can be maintained. Such tethered system is usually called electrodynamic tether system (EDTS).

The theoretical developments carried out to date and tests carried out in open space suggest that EDTS can be used as sources of Ampere force via interaction between the current and the geomagnetic field. Therefore, EDTS can provide deceleration without the need for propellant and may be used as a non-chemical thruster in near-Earth space[1]. In particular, the EDTS can be used as a promising source of drag force, which does not require fuel consumption, to solve the actual problem of debris deorbiting[1-5]. The tether stretched in near-Earth space along the local vertical is most effective[1, 2]. This orientation of the tether is stable in the central Newtonian gravitational field[1-6], but under the action of the moment of Ampere forces, the vertical orientation of the tether is destroyed[1,5]. The problem of the EDTS instability is known and is considered by experts as critically importan [4]. Among the possible approaches to solving this problem are various options for using devices to periodically turn off the current flowing along a tether[5]. However, in most cases, the EDTS should operate under conditions that imply a continuous current flow along the tether in one direction, for example, to create the drag force mentioned above in order to remove space debris. Therefore, the periodic shutdown of the current flowing through the tether or switching the direction of the current reduces the efficiency of EDTS and limits their use.

In work[7], a device for stabilizing the EDTS was proposed, which does not require a control system for the strength of the current flowing through the tether and based on charge separation at the ends of the tether and using the Lorentz torque [8,9] as an additional stabilizing torque[10-17]. The device proposed in[7] creates a restoring torque used to stabilize the EDTS. The existence and stability of the equilibrium position of the tether in a tensioned state along the local vertical is proved. However, to ensure the asymptotic stability of the vertical position of the tether, along with the restoring, a dissipative torque[18,19] is also required, the implementation method of which was not considered in [7].

In this paper, we propose an approach to the synthesis of an active control torque of a dissipative nature and a constructive scheme of the corresponding device, allowing solving the problem of stabilizing the EDTS in a state of orientation along the local vertical. It is shown that if the charge on one of the collectors is changed in accordance with the conditions determined by the current attitude motion of the tether, then it is possible to ensure the asymptotic stability of the attitude position of the tether along the local vertical. The proposed device for active damping of tether oscillations allows increasing the efficiency and operational speed of the EDTS stabilization system without the need to turn off the electric current flowing along the tether.

The interaction of the EDTS with the near-Earth plasma environment is an essential point of the problem. This point is addressed in the paper.

II. ELECTROMAGNETIC TETHER SCHEME

A scheme of EDTS is shown in Fig.1. Surface 1 is located at the lower end of the tether, which is closer to the Earth. It receives a negative charge supported by an

Corresponding author: Alexey Alexandrovich Tikhonov
e-mail address: a.tikhonov@spbu.ru
Presented at the XI International Symposium on Electrohydrodynamics (ISEHD 2019) in St. Petersburg, Russia, June 18-22, 2019
Submitted: Sep. 26, 2019, Accepted: Dec. 11, 2019

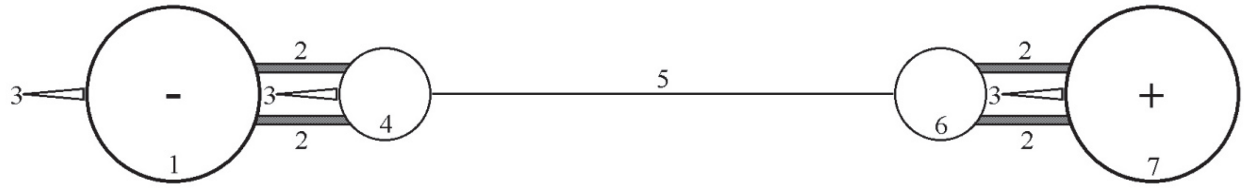

Fig. 1. Electrodynamic tether scheme

electronic emitter 3 (for example, a Hall ion source) from the end body 4. Similarly, electronic emitter 3 installed on surface 1 allows one to control the magnitude of charge on the surface 1, dropping part of the charge from the surface 1 into the surrounding space. Using electrically insulating mounts 2, the surface 1 is connected to the end body 4 of the conductive tether 5. At the opposite end of the tether, the body 6 is similarly connected to the positively charged surface 7. The positive charge on the surface 7 is supported by an electronic emitter 3 transmitting a negative charge to the end body 6.

III. Estimate of Equilibrium Characteristics

The proposed system configuration, which includes two collectors connected by a tether, assumes that the current through the tether flows due to the electromotive force arising from the motion of the tether in the Earth's magnetic field. Since the presence of electric charges on the collectors prevents current from flowing along the tether, it is necessary to use a sufficiently long tether with low resistivity to maintain a significant current in the tether. In order to ensure a better circuit of the current through the surrounding cosmic plasma[20], in many articles it is proposed to use plasma contactor, for example, based on hollow cathodes. However, their use for this system configuration is not possible, since the placement of the contactor on the upper collector is structurally difficult, and a negative charge must be discharged from the lower collector (negatively charged), which the contactor cannot provide. Therefore, it is assumed that an electron gun is located on a negatively charged collector, which injects an electron beam with energy above 10 keV and a controlled current value.

Assuming that the neutralizing currents on the collectors are completely absorbed by them and the current losses in the collectors can be neglected, we write two current balance equations for the upper and lower collectors and the Ohm's law equation for the circuit section for the current in the tether

$$\begin{gathered} I_a - I_{e2} + I_{i2} = 0, \\ -I_a - I_b + I_{i1} - I_{e1} = 0 \\ I_a R_w = \varphi_1 - \varphi_2 + E \end{gathered} \tag{1}$$

Here I_a is the tether current, I_{e1} and I_{e2} are the currents of electrons to the lower and upper collectors, respectively, I_{i1} and I_{i2} are the currents of ions to the lower and upper collectors, respectively, I_b is the currents of electrons in the electron gun, R_w is the resistance of the wire, φ_1 and φ_2 are the electric potentials of the lower and upper collectors, respectively, $E = BlV_C$ is the electromotive force in the tether, B is the geomagnetic field induction[1,21-23], l is the tether length, V_C is EDTS velocity with respect to the geomagnetic field.

The study of system (1) was carried out under the assumption that the collectors are spherical surfaces of the same radii R. The solution of system (1) gives the locally equilibrium values of potentials and currents for given values of B, l, V_C, and R.

The choice of possible values of electric charges on the collectors is due to two contradictory requirements: an increase in charges to increase the stability of the EDTS, and a decrease in charges to prevent the possibility of breakdowns and discharges. In this case, the potential of the order of 1 kV becomes the most suitable. For such potentials at the collectors, the currents I_{i2} and I_{e1} can be neglected.

Since plasma electrons at the considered heights are essentially "glued" to the geomagnetic field lines, the model proposed in [24] by L.W. Parker and B.L. Murphy was used to calculate the neutralizing current I_{e2} on a positively charged balloon. For a cylindrical spacecraft, a similar approach was applied by us in [25]. According to this model, the current of plasma electrons collected on a charged sphere increases due to electron drift across the geomagnetic field lines.

Let us estimate the drift current I_{e2} of plasma electrons. According to the drift theory, in a cylindrical coordinate system whose center coincides with the center of the sphere, and the z axis is directed along the geomagnetic field induction, the radial v_r and axial v_z components of the drift velocity of the guiding center are related by [24]

$$v_r = -\frac{v_z}{m_e \omega^2} \frac{\partial^2 \Phi}{\partial r \partial z} \tag{2}$$

where m_e and ω are the mass and gyrofrequency of electrons, respectively,

$$\Phi(r,z) = \Phi_0 a / \left(r^2 + z^2\right)^{1/2}$$

is the electrostatic potential energy of electrons, and Φ_0 is the value of Φ on the surface of balloon. For a charged sphere of radius a and an axially symmetric function $\Phi(r,z)$ for the Coulomb field of the sphere, one can get from (2) the equation for the radius of the electron collection zone at infinity [24]

$$\frac{dr}{dz} = -\frac{\alpha \cdot a^3 \cdot r \cdot z}{\left(r^2 + z^2\right)^{5/2}}. \qquad (3)$$

Here $\alpha = {3 \cdot \Phi_0} / {\left(m_e \omega^2 a^2\right)}$, $r_0 = r|_{z \to \infty}$. The solution of (3) allows one to find the current of electrons to sphere $I_{e2} = I_0 \left({r_0}/{a}\right)^2$, where $I_0 = I_0(N_e, T_e)$ is the current to an uncharged sphere, N_e is plasma density and T_e is plasma temperature. As the results of [26] show, around a negatively charged body moving in the ionosphere, a region of positive space charge arises, where the average thermal velocity of ions is less than the body velocity. In this case, the following formulae were used to calculate the neutralizing current[26]:

$$I_{i1} = 4\pi R^2 |e| n_i\left(R_*, R\right) v_i\left(R_*, R\right),. \qquad (4)$$

$$v_i\left(R_*, R\right) = -\omega_{0i} R_* \sqrt{\frac{2}{3}\left(\frac{R_c^3}{R_*^3} - 1\right)\left(\frac{R_*}{R} - 1\right)}$$

$$n_i(R_*, R) = n_i^0 \frac{R_*^3}{R^3} \frac{1 - {R_*^3}/{R_c^3}}{1 - \frac{R_*^3}{R_c^3} + \frac{3}{2}\left(\frac{R}{R_*}\sqrt{\frac{R_*}{R} - 1} + arctg\sqrt{\frac{R_*}{R} - 1}\right)\frac{R}{R_*}\sqrt{\frac{R_*}{R} - 1}}$$

Here ω_{0i} is the plasma frequency for ions, e is the electron charge, R is the radius of the sphere, R_c is the radius of the space charge region, R_* is the distance to the center of the sphere, where function $v_i\left(R_*, R\right)$ reaches its maximum, n_i^0 is unperturbed plasma ion density.

For definiteness, the joint solution of equations (1), (3) and (4) was carried out for a EDTS moving in a circular orbit in the plane of the geomagnetic equator at altitudes of 500, 600, 800 and 1000 km above the Earth's surface.

Since the plasma density N_e and temperature T_e strongly affect electron collection efficiency[27] and at the same time they change as the EDTS moves along the trajectory, system of (1), (3) and (4) was solved for values N_e and T_e taken from the IRI-2012 model[28] and for given values of latitude, longitude, height above the Earth and local time.

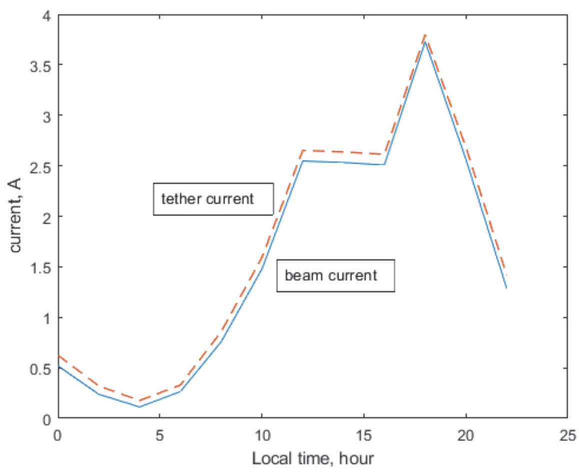

Fig. 2. Currents time history.

Fig. 2 shows the dependences of the currents in the tether and the current of the electron gun for zero latitude, 30 degrees east longitude, altitude of 550 km, and different values of local time from 0 to 22 hours.

IV. Conclusion

The article describes the functioning of a tethered system with a mixed system of charge neutralization: passive on the upper cylinder and active (electron gun) on the lower one. A significant difference between this work and other works is the use of not the averaged parameters of the surrounding plasma, but the real parameters, which vary greatly during the motion of the tethered system.

The results showed that during continuous operation of the gun, the locally equilibrium values of the potentials of the collectors and the charges on them can vary by a factor of 2 to 3, and the values of the currents in the tether and in the gun can change by more than one order of magnitude. Since it is very difficult to technically implement such an electron gun, it will be necessary to implement a pulsed mode of its operation. Problems need to be addressed further on how the system will be stabilized in the pulsed mode of the electron gun, and how efficiently it will work as a device for removing space debris.

Acknowledgment

The reported study was partially funded by the Russian Foundation for Basic Research according to the research project No. 19-01-00146-a.

Appendix

Let us briefly describe the method of obtaining formula (4). It was assumed in [26] that at the initial instant of time, the electric charge on a spherical body of radius *r* placed in the ionospheric plasma is negative, and plasma electrons in the spherical layer of thickness Δ are "swept" from the vicinity of the body. It is assumed that the total charge inside the space charge region of radius R_c is equal to zero:

$$Q_0(t) + 4\pi |e| \int_{R_0}^{R_c} n_i(R,t) R^2 dR = 0 \qquad \text{(A1)}$$

Since (A1) is the integral of motion, using the system of equations of the one-liquid quasihydrodynamic approximation and the Gaussian theorem for calculating the electric field strength in the space charge region to study the dynamics of plasma ions, it is possible to obtain expressions for the density n_i and velocity v_i of the neutralizing flux in (4). Then, (4) simply follows from the spherical symmetry of the problem.

REFERENCES

[1] V. V. Beletsky and E.M. Levin, *Dynamics of Space Tether Systems – Advances in the Astronautical Sciences*, 83 (American Astronautical Society, San Diego, California, 1993).

[2] R. L. Forward and R. P. Hoyt, "Terminator Tether: a spacecraft deorbit device," *Journal of Spacecraft and Rockets*, vol. 37, pp. 187–196, 2000.

[3] G. Sanchez-Arriaga, J. R. Sanmartin, E. C. Lorenzini, "Comparison of technologies for deorbiting spacecraft from low-earth-orbit at end of mission," *Acta Astronautica*, vol. 138, pp. 536–542, 2017.

[4] L. Iess, C. Bruno, C. Ulivieri, U. Ponzi, M. Parisse, G. Laneve, G. Vannaroni, M. Dobrowolny, F. De Venuto, B. Bertotti, L. Anselmo, "Satellite de-orbiting by means of electrodynamic tethers. Part I: general concepts and requirements," *Acta Astronautica*, vol. 50, pp. 399–406, 2002.

[5] J. Corsi, L. Iess, "Stability and control of electrodynamic tether for de-orbiting applications," *Acta Astronautica*, vol. 48, pp. 491–501, 2001.

[6] A. V. Doroshin, "Regimes of regular and chaotic motion of gyrostats in the central gravity field," *Communications in Nonlinear Science and Numerical Simulation*, vol. 69, pp. 416-431, 2019.

[7] A. A. Tikhonov, L. F. Shcherbakova, On equilibrium positions and stabilization of electrodynamic tether system in the orbital frame, *AIP Conference Proceedings*, vol. 1959, 040023, 2018.

[8] K. G. Petrov, A. A. Tikhonov, "The moment of Lorentz forces, acting upon the charged satellite in the geomagnetic field. Part 1. The strength of the Earth's magnetic field in the orbital coordinate system," *Vestnik of St.Petersburg State University*, Ser. 1, no. 1, pp. 92–100, 1999.

[9] K. G. Petrov, A. A. Tikhonov, "The moment of Lorentz forces, acting upon the charged satellite in the geomagnetic field. Part 2. The determination of the moment and estimations of its components," *Vestnik of St.Petersburg State University*, Ser. 1, no. 3, pp. 81–91, 1999.

[10] A. A. Tikhonov, "Secular evolution of rotary motion of a charged satellite in a decaying orbit," *Cosmic Research*, vol. 43, pp. 107–121, 2005.

[11] K. A. Antipov, A. A. Tikhonov, "Electrodynamic Control for Spacecraft Attitude Stability in the Geomagnetic Field," *Cosmic Research*, vol. 52, pp. 472–480, 2014.

[12] A. Y. Aleksandrov, K. A. Antipov, A. V. Platonov, A. A. Tikhonov, "Electrodynamic attitude stabilization of a satellite in the Konig frame," *Nonlinear Dynamics*, vol. 82, pp. 1493–1505, 2015.

[13] A. Y. Aleksandrov, K. A. Antipov, A. V. Platonov, A. A. Tikhonov, "Electrodynamic Stabilization of Artificial Earth Satellites in the Konig Coordinate System," *Journal of Computer and Systems Sciences International*, vol. 55, pp. 296–309, 2016.

[14] A. Y. Aleksandrov, A. A. Tikhonov, "Asymptotic stability of a satellite with electrodynamic attitude control in the orbital frame," *Acta Astronautica*, vol. 139, 122–129, 2017.

[15] A. A. Tikhonov, K. A. Antipov, D. G. Korytnikov, D. Yu. Nikitin, "Electrodynamical compensation of disturbing torque and attitude stabilization of a satellite in J2 perturbed orbit," *Acta Astronautica*, vol. 141, 219–227, 2017.

[16] D. Y. Nikitin, A. A. Tikhonov, "Attitude Stabilization of a Spacecraft Equipped with Large Electrostatic Protection Screens," *AIP Conference Proceedings*, vol. 1959, 040011, 2018.

[17] A. Yu. Aleksandrov, E. B. Aleksandrova, A. A. Tikhonov, "Stabilization of a programmed rotation mode for a satellite with electrodynamic attitude control system," *Advances in Space Research*, vol. 62, pp. 142–151, 2018.

[18] P. S. Krasil'nikov, A. Y. Maiorov, "On the Stability of Equilibrium of a Mechanical System with Tracking, Potential, and Small Dissipative Forces," *Mechanics of Solids*, vol. 53, pp. 52-59, 2018.

[19] M. V. Shamolin, "Comparison of Jacobi-integrable cases of the plane and three-dimensional motion of a body in a medium in the case of jet flow," *Journal of Applied Mathematics and Mechanics*, vol. 69, no. 6, pp. 900–906, 2005.

[20] A. Mizuno, K. Takashima, Y. Kinoshita, "Possible relation between atmospheric ionic current and earthquake," *International Journal of Plasma Environmental Science and Technology*, vol. 5, no. 1, pp. 99-101, 2011.

[21] A. Toureille, G. Touchard, and A. Mizuno, "Geomagnetism due to a piezo electrical activity of D" layer," *International Journal of Plasma Environmental Science and Technology,* vol. 5, pp. 80-83, 2011.

[22] A. Toureille, "Justifications of a New Theory of Geomagnetism," *International Journal of Plasma Environmental Science and Technology*, vol.9, no.2, pp.114-119, 2015.

[23] M. Y. Ovchinnikov, V. I. Penkov, D. S. Roldugin, A. V. Pichuzhkina, "Geomagnetic field models for satellite angular motion studies," *Acta Astronautica*, vol. 144, pp. 171–180, 2018.

[24] L. W. Parker, B. L. Murphy, "Potential buildup on an electron-emitting ionospheric satellite," J. Geophys. Res., vol. 72, pp. 1631–1636, 1967.

[25] E. K. Kolesnikov, A. B. Yakovlev, "Procedure for calculating the electric field strength induced near the surface of an infinite cylinder that rests in a collisionless plasma in a homogeneous magnetic field, the charge flow from surface being fixed," *Cosmic Research*, vol. 34, no. 6, pp. 615–616, 1996.

[26] V. A. Fedorov, "Neutralization of negative electric charge of a satellite by ionospheric plasma ions," *Cosmic Research*, vol. 43, pp. 7–16, 2005. DOI: 10604-005-0014-8.

[27] S. Kawamoto, T. Makida, F. Sasaki,Y. Okawa, "Precise numerical simulations of electrodynamic tethers for an active debris removal system," *Acta Astronautica*, vol.59, pp.139–148, 2006.

[28] The International Reference Ionosphere [Online] Available: http://irimodel.org/