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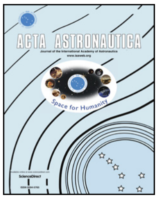

Libration dynamics of electrodynamic tether system for 13 degrees International Geomagnetic Reference Field

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ABSTRACT

The libration dynamics of the electrodynamic tether system is studied for 13° International Geomagnetic Reference Field. Using the International Geomagnetic Reference Field including up to 13 t h order and 13° terms to describe the geomagnetic field, the attitude dynamic equations of the system in the elliptical orbits are built. The generalized forces produced by this magnetic model are derived. The generalized forces related to the in-plane and out-of-plane angles are sum of generalized forces for nontilted dipole model and generalized forces for higher order geomagnetic model terms. In the analysis of the libration dynamic characteristics, the generalized forces for higher order geomagnetic model terms are regarded as perturbations to the dynamic equations for the nontilted dipole model. The simulation results show that differences of components of these two geomagnetic model and differences of generalized forces related to them are all small. Failure time of the libration motion is defined to measure the influence of the perturbation to the system. Examples for different electrodynamic parameters and orbital parameters are simulated. The results show that the perturbations have obvious effects on the attitude dynamics. The influences of perturbations caused by higher order terms of 13° International Geomagnetic Reference Field for different parameters are all obtained.

1. Introduction

Electrodynamic tether system (EDT) is a spacecraft system which consists of two satellites and a flexible and conducting tether [1]. The satellites are connected to the ends of the tether. Interacting with the geomagnetic field and the ionosphere, the EDT can produce Lorenz force which can be used for orbital maneuver. The EDT has advantages of propellantless, light weight and large power [2–5]. It has shown great potential in formation flying, orbital maneuvering and space debris removal [6–9].

For deorbiting spacecraft from Low-Earth-Orbit (LEO) at end of mission, Sánchez-Arriaga et al. [2] compared the EDT with other three technologies: rockets, electrical thrusters and drag augmentation devices. The result shows that EDT may dominate other technologies in terms of performance and reliability. Hoyt [4] used the EDT to provide power to spacecraft systems by "harvesting" energy from the system's orbit. He presented results of detailed simulations of the performance of an EDT propulsion system sized for microsatellite-class systems in LEO over a range of inclinations. Ishige et al. [5] outlined the phases of the mission and conducted a number of simulations to assess the viability of EDT systems in debris repair and removal mission. It is found that EDT systems can transfer satellites from LEO to orbits with a short lifetime within a realistic timeframe. Zhu and Larouche [9] presented a design of an EDT nanosatellite mission which covered the mission concept study, mission objectives, nanosatellite design, hardware selection, and operation. The proposed mission can provide a novel and almost 'free' approach, which is inaccessible on Earth for the radio scientists.

The attitude libration dynamics of EDT is an important issue for the future use of tether in space [10–13]. To investigate the libration dynamics of EDT, Peláez and Lara [14] first put forward the dumbbell model and derived the attitude dynamic equations for an EDT system running in the circular orbit. The attitude dynamic equations for the EDT in the elliptical orbit were presented by Peláez and Andrés in Ref. [15]. The EDT's attitude equations for both circular and elliptical orbit are all strongly nonlinear. There is no singular point for the nonlinear attitude dynamic equations, but periodic solutions exist for them in suitable range of parameter values. The periodic solutions can be obtained using numerical methods such as Poincaré continuation method and Legendre pseudospectral method [15,16]. The periodic solutions are unstable, and the instability grows with increasing electrodynamic parameter and orbital eccentricity [15].

The unstable periodic libration motions will become irregular and tumbling motions if perturbation exists. The regular periodic attitude librations have unique meanings for the EDT running in the orbit. The

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Nomenclature

a	Radius of the Earth, m
$\boldsymbol{B}$	Geomagnetic field, T
$\boldsymbol{B}_I$	Geomagnetic field vector in the inertial Earth coordinate, T
	Geomagnetic field vector in the orbital coordinate, T
B_r, B_λ, B_φ	Components of geomagnetic field vector in the spherical coordinate system, T
$B_{x'}B_{y'},B_{z'}$	Components of geomagnetic field vector in the North East geodetic coordinate, T
B_x, B_y, B_z	Components of geomagnetic field vector in the orbital coordinate, T
B_x^{13}, B_y^{13}, B_z^{13}	Components of 13° IGRF in the orbital coordinate, T
B_x^1, B_y^1, B_z^1	Components of the nontilted dipole magnetic field in the orbital coordinate, T
$\boldsymbol{C}_N^I$	Transfer matrix of the North East geodetic coordinate system to the inertial Earth coordinate system
$\boldsymbol{C}_I^O$	Transfer matrix of the inertial Earth coordinate system to the orbital coordinate system
$\mathrm{d}s$	Differential length element
e	Orbital eccentricity
$EXYZ$	Inertial geocentric frame
g_n^m,h_n^m	Gaussian coefficients for the IGRF
h	Altitude of the perigee, m
i	Orbital inclination, rad
$I(s)$	Electric current, A
$\bar{I}$	Tether current averaged over the total length, A
$\boldsymbol{i}\,\boldsymbol{j},\boldsymbol{k}$	Basis of the orbital frame
l	Tether length, m
m_1	Main-satellite mass, kg
m_2	Sub-satellite mass, kg
M	Total mass of the system, kg
m^*	Reduced mass of the system, kg
$Ox'y'z'$	North East geodetic coordinate system
$Oxyz$	Orbital coordinate system
V	Potential function of the geomagnetic field
P_n^m	Schmidt quasi-normalized associated Legendre functions
Q_θ, Q_ϕ	Generalized torque relative to θ,ϕ respectively, N·m
$Q_{\theta 1}$, $Q_{\phi 1}$	Generalized torque for the nontilted dipole magnetic field, N·m
$Q_{\theta 2}$, $Q_{\phi 2}$	Generalized torque for higher order terms of IGRF, N·m
r	Orbital radius, m
$\boldsymbol{R}$	Position vector of ds, m
$\boldsymbol{t}$	Unit tangent vector along the tether
u	Argument of perigee, rad
α	Right ascension of spacecraft, rad
δ	Declination of spacecraft, rad
ε	Electrodynamic parameter
φ	Longitude, rad
λ	Co-latitude, rad
ϕ	Out-of-plane libration angle, rad
θ	In-plane libration angle, rad
Ω	Right ascension of the ascending node of the orbit, rad
μ_m	Magnetic field strength, T·km^3
μ	Earth's gravitational parameter, m^3/s^2
ν	Orbital true anomaly, rad
ω	Orbital angular velocity, rad/s
(.)	d( )/dν

stabilized periodic attitude motions can be taken as starting states for the opretion of the tether. They can be taken as reference orbits for stability control, and they represent the ideal cases of zero net energy pumped into the system per orbit [17,18]. A variety of instability analysis and control methods of periodic solutions have been developed over the past several years [19–24]. Kojimaa and Sugimotob [21,22] used two control methods to stabilize the in-plane/out-of-plane coupling librational motion of EDT systems in inclined elliptic with high eccentricity to a periodic motion. Larsen and Blanke [23] designed a passivity-based control law to stabilize the periodic solutions by controlling only the current through the tether. Stability properties of the system are investigated using the Floquet analysis, and the region of stability is found in the plane defined by the control parameters. Iñarrea et al. [24] studied the application of two time-delayed feedback control methods in order to stabilize the periodic attitude motions of EDT in the inclined elliptical orbits.

In all of the aforementioned work about dynamics model building, dynamics analysis and control, the nontilted dipole model of the geomagnetic field is usually adopted in evaluating the electrodynamic force. The perturbations resulting from the irregular variation of the geomagnetic field is ignored. However, the actual geomagnetic field is much more complex than the nontilted dipole model which is the simplest geomagnetic field model. The magnetic field is one of the most important factors in evaluating the electrodynamic force. So the geomagnetic field model should be modified in order to reflect a more realistic model of the system. The electric field is another important factor for the EDT. Sheikholeslami et al. [25,26] give the governing formula and definition of electric field and apply the electric field for improving heat transfer of nanofluid. However, this paper mainly focuses on the effect of the magnetic field on the EDT. The details of the electric field are outside the scope of this paper.

At present, the accepted model for the geomagnetic field is the International Geomagnetic Reference Field (IGRF), put forth by the International Association of Geomagnetism and Aeronomy (IAGA) [27]. The IGRF model expanded to increase the precision of the coefficients to one-tenth of a nanoTesla and increased the number of coefficients to 13°. In this paper, the IGRF model with up to 13 t h order and 13° is taken as the geomagnetic field model to evaluate the electrodynamic force for the libration dynamics of the EDT. The attitude libration dynamics for the 13° IGRF will be studied and compared with libration dynamics for the nontilted dipole magnetic model.

This paper contains three logical stages. Firstly, 13° IGRF is introduced, and the generalized forces corresponding to the generalized coordinates are evaluated. Next, the attitude dynamic equations for 13° IGRF are derived and written in the form of libration equations for the nontilted dipole geomagnetic field model with perturbations of electrodynamic force. Finally, the differences between generalized forces corresponding to 13° IGRF and the nontilted dipole model are simulated. The characteristics of attitude dynamic equations for 13° IGRF are simulated for different values of electrodynamic parameter, orbital eccentricity, orbital inclination and attitude of orbit.

2. Mathematical models

2.1. Coordinate systems

The coordinate systems used in this paper are shown in Fig. 1 and introduced as follows:

2.1.1. The spherical coordinate frame

The origin point locates at the center of mass of the Earth. The polar