Lecture Notes in Electrical Engineering 917

Jiande Sun
Yue Wang
Mengyao Huo
Lexi Xu *Editors*

Signal and Information Processing, Networking and Computers

Proceedings of the 8th International Conference on Signal and Information Processing, Networking and Computers (ICSINC)

Springer

Lecture Notes in Electrical Engineering

Volume 917

The book series *Lecture Notes in Electrical Engineering* (LNEE) publishes the latest developments in Electrical Engineering - quickly, informally and in high quality. While original research reported in proceedings and monographs has traditionally formed the core of LNEE, we also encourage authors to submit books devoted to supporting student education and professional training in the various fields and applications areas of electrical engineering. The series cover classical and emerging topics concerning:

- Communication Engineering, Information Theory and Networks
- Electronics Engineering and Microelectronics
- Signal, Image and Speech Processing
- Wireless and Mobile Communication
- Circuits and Systems
- Energy Systems, Power Electronics and Electrical Machines
- Electro-optical Engineering
- Instrumentation Engineering
- Avionics Engineering
- Control Systems
- Internet-of-Things and Cybersecurity
- Biomedical Devices, MEMS and NEMS

For general information about this book series, comments or suggestions, please contact leontina.dicecco@springer.com.

To submit a proposal or request further information, please contact the Publishing Editor in your country:

China

Jasmine Dou, Editor (jasmine.dou@springer.com)

India, Japan, Rest of Asia

Swati Meherishi, Editorial Director (Swati.Meherishi@springer.com)

Southeast Asia, Australia, New Zealand

Ramesh Nath Premnath, Editor (ramesh.premnath@springernature.com)

USA, Canada:

Michael Luby, Senior Editor (michael.luby@springer.com)

All other Countries:

Leontina Di Cecco, Senior Editor (leontina.dicecco@springer.com)

**** This series is indexed by EI Compendex and Scopus databases. ****

More information about this series at https://link.springer.com/bookseries/7818

Jiande Sun · Yue Wang ·
Mengyao Huo · Lexi Xu
Editors

Signal and Information Processing, Networking and Computers

Proceedings of the 8th International Conference on Signal and Information Processing, Networking and Computers (ICSINC)

Springer

Editors
Jiande Sun
School of Information Technology
and Engineering
Shandong Normal University
Jinan, China

Mengyao Huo
Beijing University of Posts
and Telecommunications
Beijing, China

Yue Wang
China Academy of Space Technology
Beijing, China

Lexi Xu
China Unicom
Haidian, Beijing, China

ISSN 1876-1100 ISSN 1876-1119 (electronic)
Lecture Notes in Electrical Engineering
ISBN 978-981-19-3386-8 ISBN 978-981-19-3387-5 (eBook)
https://doi.org/10.1007/978-981-19-3387-5

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

Preface

It is our great honor to welcome you to the 8th International Conference on Signal and Information Processing, Network and Computers (ICSINC 2021). The ICSINC 2021 Committee has been monitoring the evolving COVID-19 pandemic. We have decided to delay the 2021 edition of this conference from May to December.

ICSINC 2021 provides a forum for researchers, engineers and industry experts to discuss recent development, new ideas and breakthrough in signal and information processing schemes, computer theory, space technologies, big data and so on.

ICSINC 2021 received 243 papers submitted by authors, and 178 papers were accepted and included in the final conference proceedings. The accepted papers will be presented and discussed in 27 regular technical sessions and two workshops.

On behalf of the ICSINC 2021 committee, we would like to express our sincere appreciation to the TPC members and reviewers for their tremendous efforts. Especially, we appreciate all the sponsors for their generous support and advice, including Springer, China Unicom, Shandong Normal University and HuaCeXinTong company. Finally, we would also like to thank all the authors for their excellent work and cooperation.

Qingliang Zeng
Songlin Sun
Yue Wang
ICSINC 2021 General Chairs

Organization

Committee Members

International Steering Committee

Songlin Sun	Beijing University of Posts and Telecommunications, China
Ju Liu	Shandong University, China
Chenwei Wang	DOCOMO Innovations (DoCoMo USA Labs), USA
Jiaxun Zhang	China Academy of Space Technology, China
Takeo Fujii	The University of Electro-Communications, Japan
Martin Haardt	Ilmenau University of Technology, Germany
Cecilia Zanni-Merk	INSA Rouen Normandie, France
Yuanjie Zheng	Shandong Normal University

General Chairs

Qingliang Zeng	Shandong Normal University
Songlin Sun	Beijing University of Posts and Telecommunications, China
Yue Wang	China Academy of Space Technology, China

Technical Program Committee Chairs

Songlin Sun	Beijing University of Posts and Telecommunications, China
Gang Sun	China Academy of Space Technology, China
Jiande Sun	Shandong Normal University, China

Publication Chairs

Xinmin Song — Shandong Normal University, China
Jia Zhang — Shandong Normal University, China

General Secretaries

Jiaqi Zou — Beijing University of Posts and Telecommunications, China
Yufeng Yan — Beijing University of Posts and Telecommunications, China

Sponsors

Springer

China Unicom

HuaCeXinTong

Shandong Normal University

Contents

Space Technology I

Averaged Equation of Satellite Relative Motion in an Elliptic Orbit

Rucai Che(✉)

Beijing Institute of Control Engineering, Beijing 100190, China
986462192@qq.com

Abstract. The precision model of relative motion is a necessity for satellite formation flying, but these models are complex for analysis and design, especially in elliptic orbit. For some satellite formation flying applications, the long-term formation maintenance and fuel-saving is more important for satellite life. Using the averaged analysis method over an orbit period, the averaged equation of satellite relative motion in an elliptic orbit is presented in this paper. Firstly, based on the homogeneous solutions of T-H equations, a simple averaged equation of relative motion is derived. Secondly, the improved averaged equation of relative motion which is described by the instantaneous orbit elements difference is developed for considering the orbital perturbation. The effectiveness of the proposed models is verified by four simulation cases which consider the orbit perturbation or not. The proposed model can eliminate the periodicity movement of satellite relative motion, and it is convenient for long-term formation flying designing and configuration controlling.

Keywords: Elliptic orbit · Satellite formation · Relative motion

1 Introduction

In recent years, there has been a growing interest in satellite formation flying and there are many space applications of formation flying, such as stereo observation, SAR interferometry etc. [1]. The earliest and most prevalent model governing relative motion is given by the Clohessy-Wiltshire (C-W) equation [2] which assumes a circular reference orbit for target satellite, providing an analytic description of relative motion. The Tschauner-Hempel (T-H) equation [3] extend the C-W model to accommodate non-circular reference orbit, by expressing the equations of motion in terms of target orbit eccentricity and initial true anomaly [4]. Currently, there have been many scientific papers written on the subjects of high precision models and configuration designing for relative motion. Katsuhiko [5] developed expansion of T-H equation which considering J2 perturbation to improve the calculating precision. Mai [6] developed a graphical analysis for T-H equation based on the period orbit. Schaub [7] proposed a new presentation which is based on the orbital elements difference. For configuration controlling of relative motion, Vadali [8] designed a digital filter to

J. Sun et al. (Eds.): *Signal and Information Processing, Networking and Computers*, LNEE 917, pp. 3–11, 2023.
https://doi.org/10.1007/978-981-19-3387-5_1

eliminate the period vibration which can reduce the fuel consumption. Balaji [9] has parameterized C-W equation in terms of mean value for configuration controlling.

There is a wealth of literature on relative motion models. Nevertheless, the averaged equation over orbit period is useful for relative motion analysis, especially for long term prediction and formation configuration designing. Based on the average calculation in an orbit period, two different averaged relative motion equations are presented in this paper. Then, the characteristic of averaged models are also been developed. The analysis thought and calculation of this method is simple, and the effectiveness of the model was proved by digital simulations.

2 Relative Motions in Two-Body Orbit

We take the orbit coordinate systems ***oxyz*** of the target satellite as the relative motion coordinate system. The origin is the center of the mass of the target satellite, and move in orbit with it. The ***x***-axis coincides with geocentric vector ***r*** of the target satellite, and points from geocenter to target satellite**.** The ***y***-axis is normal to ***x***-axis in the orbit plane, and points to the direction of motion. The *z*-axis determined by right-hand rule, coincides with the angular momentum vector of the target satellite. The relative motion

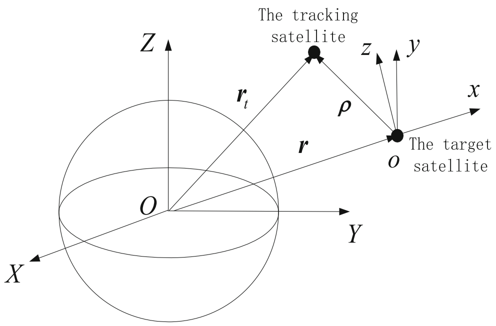

Fig. 1. The ***oxyz*** and ***OXYZ*** coordinate.

coordinate system ***oxyz*** and geocentric inertial coordinate system ***OXYZ*** is shown in Fig. 1.

2.1 Relative Motion Model and Analytical Equation

Consider two satellites in elliptical orbits about a common gravitational source, as shown in Fig. 1. Employing the common designations associated with relative motions, tracking satellite denotes the second satellite, moving close to the target and with position $\boldsymbol{r}_t$.

By form the relative position vector $\boldsymbol{\rho} = [x\,y\,z]^{\mathrm{T}}$. Based on the condition of $\rho << r$, the relative motion equation in two-body orbit can be described by [4].

$$\begin{bmatrix} x'' \\ x' \\ y'' \\ y' \end{bmatrix} = \begin{bmatrix} \frac{2e\sin f}{\lambda_f} & 1+\frac{2}{\lambda_f} & 2 & -\frac{2e\sin f}{\lambda_f} \\ 1 & 0 & 0 & 0 \\ -2 & \frac{2e\sin f}{\lambda_f} & \frac{2e\sin f}{\lambda_f} & \frac{e\cos f}{\lambda_f} \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} x' \\ x \\ y' \\ y \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} z'' \\ z' \end{bmatrix} = \begin{bmatrix} \frac{2e\sin f}{\lambda_f} & -\frac{1}{\lambda_f} \\ 1 & 0 \end{bmatrix} \begin{bmatrix} z' \\ z \end{bmatrix} \tag{2}$$

where $\lambda_f = 1 + e\cos f$, e is the eccentricity of target satellite, f is true anomaly of target satellite, $(\cdot)' = d(\cdot)/df$. In two body orbit, the analytical model of Eq. 1 can be written as follows [4]:

$$\left.\begin{aligned} x(f) &= [d_1 e + 2d_2 e^2 H(f)]\sin f - (d_2 e\lambda_f^{-2} + d_3)\cos f \\ y(f) &= d_3(1+\lambda_f^{-1})\sin f + [d_1 e + 2d_2 e^2 H(f)]\cos f + \left[d_1 + d_4\lambda_f^{-1} + 2d_2 eH(f)\right] \\ z(f) &= d_5\lambda_f^{-1}\sin f + d_6\lambda_f^{-1}\cos f \end{aligned}\right\} \tag{3}$$

$$\left.\begin{aligned} x'(f) &= [d_2 e\lambda_f^{-2} + d_3]\sin f + [d_1 e + 2d_2 e^2 H(f)]\cos f \\ y'(f) &= \left[d_3 e\lambda_f^{-2}\sin f + d_4 e\lambda_f^{-2} - d_1 e - 2d_2 e^2 H(f)\right]\sin f + \left[d_3(1+\lambda_f^{-1}) + 2d_2 e\lambda_f^{-2}\right]\cos f \\ z'(f) &= (d_5 e\lambda_f^{-2}\sin f - d_6\lambda_f^{-1})\sin f + (d_5\lambda_f^{-1} + d_6 e\lambda_f^{-2}\sin f)\cos f \end{aligned}\right\} \tag{4}$$

where $d_i(i = 1, \ldots, 6)$ is the integral constant, $H(f)$ is integral expansion item.

2.2 The Averaged Equation of Relative Motion

It is well known that typical character of the T-H equations is periodicity of orbit because each equation contains trigonometric function. For applications to surveillance, the first goal is to survey the averaged equation in an orbit period.

Because the integral expansion item $H(f)$ is very complex, and it is difficult to directly calculate the average equation. Nevertheless, the series of $H(f)$ can be used to express the equations. Based on the power series

$$\lambda_f^m = (1 + e\cos f)^m = 1 + me\cos f + \cdots + \frac{m(m-1)\cdots(m-n+1)}{n!} e^n \cos^n f + \cdots \tag{5}$$

The integral expansion item $H(f)$ can be rewritten as

$$H(f) = \sin f - 3e[\frac{f}{2} + \frac{\sin 2f}{4}] + 6e^2[\sin f + \frac{\sin^3 f}{3}] - 10e^3[\frac{3f}{8} + \frac{3}{16}\sin 2f + \frac{\sin f\cos^3 f}{4}] + \cdots - H_{f_0} \tag{6}$$

where

$$H_{f_0} = \sin f_0 - 3e[\frac{f_0}{2} + \frac{\sin 2f_0}{4}] + 6e^2[\sin f_0 + \frac{\sin^3 f_0}{3}] - 10e^3[\frac{3f_0}{8} + \frac{3}{16}\sin 2f_0 + \frac{\sin f_0 \cos^3 f_0}{4}] + \cdots \tag{7}$$

f_0 is the true anomaly at initial time. For satellites in low earth orbit, e^4 and higher items are very small which can be omitted in calculation. The Eq. 7 can be approximated as

$$H(f) \approx \sin f - 3e[\frac{f}{2} + \frac{\sin 2f}{4}] + 6e^2[\sin f - \frac{\sin^3 f}{3}] - 10e^3[\frac{3f}{8} + \frac{3}{16}\sin 2f + \frac{\sin f \cos^3 f}{4}] - H_{f_0} \tag{8}$$

Then, the x-axis averaged motion in an orbit period can be calculated as

$$\bar{x} = \frac{1}{2\pi}\int_0^{2\pi} \left\{ \left[d_1 e + 2d_2 e^2 H(f) \right] \sin f - (d_2 e \lambda_f^{-2} + d_3) \cos f \right\} df \tag{9}$$

Substituting Eq. 8 into Eq. 9, omitting e^4 and higher order items, we obtain

$$\begin{aligned} \bar{x} &\approx \tfrac{d_2 e}{2\pi} \int_0^{2\pi} \left\{ 2e\left[\sin^2 f - 3e(\tfrac{f \sin f}{2} + \tfrac{\sin f \sin 2f}{4}) \right] - 2e \sin f H_{f_0} - \cos f [1 - 2e \cos f + 3e^2 \cos^2 f] \right\} df \\ &= (2e^2 + 3e^3) d_2 \end{aligned} \tag{10}$$

In the same way the averaged relative position and averaged relative velocity in y-axis and z-axis can be obtained

$$\left. \begin{aligned} \bar{x} &= (2e^2 + 3e^3) d_2 \\ \bar{y} &= d_1 - (3e^2\pi + 2eH_{f_0}) d_2 + (1 + \tfrac{e^2}{2}) d_4 \\ \bar{z} &= -(\tfrac{e}{2} + \tfrac{3e^3}{8}) d_6 \end{aligned} \right\} \tag{11}$$

$$\left. \begin{aligned} \bar{x}' &= 0 \\ \bar{y}' &= [-3e^2 - 6e^3] d_2 \\ \bar{z}' &= 0 \end{aligned} \right\} \tag{12}$$

The averaged equations, Eq. 11 and Eq. 12, are simple and convenient for analysis and designing. In two-body elliptical orbit, if $d_2 \neq 0$, the relative motion in along-track direction is not closed. The averaged drift velocity in y-axis is $\bar{y}'$, which can be decided by eccentricity and initial constant d_2. The mean velocity in x-axis and z-axis is zero, which is correspond to the relative motion.

3 Averaged Equation of Relative Motion with Orbital Perturbation

For LEO satellite, the earth's non-spherical shape and atmosphere perturbation greatly affects the relative motion of satellite. The perturbations make the satellite rotate or drift, and the relative motion will not be closed. Equation 11 and Eq. 12 are not convenient to analyze the orbital perturbation, so the orbital elements will be considered in this section.

We denote

$$\left.\begin{aligned}\boldsymbol{\sigma} &= (a, e, i, \omega, \Omega, M)^{\mathrm{T}}\\ \boldsymbol{\sigma}_t &= (a_t, e_t, i_t, \omega_t, \Omega_t, M_t)^{\mathrm{T}}\end{aligned}\right\} \tag{13}$$

where a is semi-major axis, e is eccentricity, i is inclination, ω is perigee anomaly, Ω is right ascension of ascending node, M is mean anomaly. The orbital element differences between the target satellite and tracking satellite defined as $\delta\boldsymbol{\sigma} = \boldsymbol{\sigma}_t - \boldsymbol{\sigma}$. Based on the relations between the integral constant d_i and the orbital element difference $\delta\boldsymbol{\sigma}_0$ [10]

$$\left.\begin{aligned}\delta a_0 = \frac{2e^2}{\eta^4}d_2,\ \delta e_0 = \frac{e}{a\eta^2}d_2 + \frac{1}{a}d_3,\ \delta\omega_0 = \frac{1}{a\eta^2}d_4 - \frac{\sin\omega\cot i}{a\eta^2}d_5 + \frac{\cos\omega\cot i}{a\eta^2}d_6\\ \delta M_0 = \frac{\eta}{a}(d_1 - 2eH_{f0}d_2),\ \delta i_0 = \frac{\cos\omega}{a\eta^2}d_5 + \frac{\sin\omega}{a\eta^2}d_6,\ \delta\Omega_0 = \frac{\sin\omega\sin^{-1}i}{a\eta^2}d_5 - \frac{\cos\omega\sin^{-1}i}{a\eta^2}d_6\end{aligned}\right\} \tag{14}$$

where $\eta = \sqrt{1-e^2}$, Eq. 11 can be rewritten as

$$\left.\begin{aligned}\bar{x} &= (1+\tfrac{3}{2}e)\eta^4\delta a_0\\ \bar{y} &= \tfrac{a}{\eta}\delta M_0 - \tfrac{3\pi\eta^4}{2}\delta a_0 + a\eta^2(1+\tfrac{e^2}{2})(\delta\omega_0 + \cos i\delta\Omega_0)\\ \bar{z} &= -(\tfrac{e}{2} + \tfrac{3e^3}{8})a\eta^2(\sin\omega\delta i_0 - \cos\omega\sin i\delta\Omega_0)\end{aligned}\right\} \tag{15}$$

Considering the orbital perturbation, the orbital element difference would not be a constant, that means $\delta\dot{\sigma} \neq \mathbf{0}$. In each calculation step, the instantaneous orbital element of satellite can be calculated in high precision. So the orbital element difference can be obtained in real time, the averaged relative motion can also be calculated by following equations.

$$\left.\begin{aligned}\bar{x}(t) &= (1+\tfrac{3}{2}e)\eta^4\delta a\\ \bar{y}(t) &= \tfrac{a}{\eta}\delta M - \tfrac{3\pi\eta^4}{2}\delta a + a\eta^2(1+\tfrac{e^2}{2})(\delta\omega + \cos i\delta\Omega)\\ \bar{z}(t) &= -(\tfrac{e}{2} + \tfrac{3e^3}{8})a\eta^2(\sin\omega\delta i - \cos\omega\sin i\delta\Omega)\end{aligned}\right\} \tag{16}$$

The time derivative of Eq. 16 can be approximated as

$$\left.\begin{aligned}\dot{\bar{x}}(t) &\approx (1+\tfrac{3}{2}e)\eta^4\delta\dot{a}\\ \dot{\bar{y}}(t) &\approx \tfrac{a}{\eta}\delta\dot{M} - \tfrac{3\pi\eta^4}{2}\delta\dot{a} + a\eta^2(1+\tfrac{e^2}{2})(\delta\dot{\omega} + \cos i\delta\dot{\Omega})\\ \dot{\bar{z}}(t) &\approx -(\tfrac{e}{2} + \tfrac{3e^3}{8})a\eta^2(\sin\omega\delta\dot{i} - \cos\omega\sin i\delta\dot{\Omega})\end{aligned}\right\} \tag{17}$$

Moreover, with the theory of the secular orbit perturbation, we can obtain the following conclusion: