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Design and optimization of low-thrust orbital phasing maneuver

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A B S T R A C T

The minimum-time orbital phasing maneuver for a spacecraft with an electric thruster is studied. An efficient preliminary design method for phasing maneuver is developed. In this design method, two phasing strategies, an outward phasing strategy and an inward phasing strategy, are proposed based on the characteristics of the phasing mission. In the case of a circular orbit, an analytical solution is obtained by introducing certain assumptions. For the case of an elliptic orbit, a semi-analytical solution is obtained using the orbital averaging technique. Using this method, significant computational time can be saved because numerical integration of the long-duration phasing trajectory is avoided. In addition, the method is improved to design the phasing maneuver for the thrust-coast-thrust case. Furthermore, a shooting iteration method is adopted to improve the solution to satisfy the terminal constraints of high-precision numerical integration. The validity and accuracy of the preliminary design method are investigated by designing a variety of phasing missions. The results lead to several major conclusions: (1) The exponent of the phasing time is linearly proportional to the exponent of the thrust acceleration; (2) For the thrust-coast-thrust case, the total phasing time increases as the coast time increases, while the thrust time decreases; (3) The proposed preliminary design method can rapidly provide good initial guesses for the phasing maneuver optimization, and the shooting iteration method converges steadily and rapidly.

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1. Introduction

This study investigates a phasing mission in which the chaser and the target spacecraft are in the same orbit. The objective of the phasing mission is to cancel out the phase angle difference between the chaser and the target spacecraft. During the phasing segment, the relative phase between the chaser and the target should be reduced using a chemical or an electric thruster.

For the case of a chemical thruster, the phasing maneuver design can be treated as an orbit design of the multi-impulse rendezvous type. Luo [15] transformed the rendezvous phasing special-point maneuvers design into a mixed one-zero, integer and continuous design variables problem and solved it with a hybrid approach that combines simulated annealing with Newton's method. Zhang [16] investigated the target phasing optimization problem. Considering the number of revolutions which the reference orbit traverses following a maneuver to be a design variable, the target phasing maneuver optimization becomes a mixed integer nonlinear programming problem. A hybrid approach, which combines branch-and-bound and sequential quadratic programming, was used to achieve an approximate solution to the problem.

In recent years, low-thrust propulsion has attracted increased attention because it can significantly reduce fuel consumption. However, using low-thrust propulsion increases the complexity of the dynamics, and the phasing would consume more time. For the low-thrust phasing mission, the design of the phasing maneuvers is commonly considered to be an optimal control problem. Traditional methods for solving the optimal control problem can be divided into three classes: direct methods [1], indirect methods [7] and hybrid methods [9]. The main idea of the direct and the hybrid methods is to transform the optimal control problem into a parameter optimization problem, and the indirect methods transform the optimal control problem to a two-point boundary value problem. Hall investigated the minimum-time orbital phasing maneuver using constant thrust, in which the initial position of the spacecraft and the target are in the same circular orbit [8]. The minimum-time phasing maneuver design problem was solved using Pontryagin's minimum principle, and several interesting characteristics of the solutions were presented. However, without a

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good initial guess, these techniques will have a long computation time and often converge to a local minimum.

To formulate a good initial guess, the usual method is to simplify the problem by making some assumptions. Edelbaum suggested that changing station using tangential thrust is the most effective approach [4]. On the basis of Edelbaum's approach, the trajectory from one circular orbit to another is optimized under the assumption of quasi-circular orbits [2,10,13]. In addition, the phasing mission between different orbits has been investigated by many researchers. Kechichian analyzed low-thrust zero-eccentricity-constrained orbit raising in a circular orbit in the presence of shadowing [11]. Numerical and analytical methods were used to solve the problem, and the results showed that the analytical method can solve the problem with small error and require less computation time. However, these preliminary design methods cannot be used in the elliptic orbit case because the quasi-circular assumption is unusable.

In this paper, based on the orbital averaging technique and the thrust direction hypothesis, an efficient preliminary design method that is suitable for both the circular and the elliptic case is proposed. Next, the trajectories are improved by a shooting method. For the shooting method, the initial guesses of adjustable variables can be easily obtained by transforming the initial design results.

The main contents of this paper is summarized as follows: Before the design method is presented, the phasing model is described in detail, and the phasing maneuver is analyzed using the characteristics of this transfer type. Based on the analysis, two simple phasing strategies, an outward phasing strategy and an inward phasing strategy, are summarized under the thrust direction hypothesis. Next, while ignoring the minor constraints, the phasing maneuver design is simplified into a problem involving the solution of nonlinear equations. An analytical expression is obtained for the circular orbit case, and a semi-analytical method using orbital averaging is obtained for the elliptic orbit case. In addition, the relationship between the accuracy of the solution and the mission parameters is studied. Furthermore, a simple numerical method is proposed to increase the accuracy for elliptic orbit case. The numerical method only contains three optimization parameters and can be rapidly solved by a Sequential Quadratic Programming (SQP) algorithm. By comparing the total phasing time of the outward phasing strategy with that of the inward phasing strategy, the phasing strategy and key parameters of the phasing maneuvers can be determined. To improve the initial design result to satisfy the terminal constraints of high-precision numerical integration, a shooting method with control-angle discretization is proposed. Finally, some examples of phasing maneuver design are presented to demonstrate the design approach.

2. Problem statement

In this section, the problem statement for a general orbital phasing mission is described in brief. As shown in Fig. 1, the chaser and target spacecraft move on the same circular or elliptic orbit around Earth. Before the phasing mission begins, the phase angle between the chaser and the target is ϕ. The aim of an orbital phasing mission is to cancel out the phase angle difference between the two spacecraft by changing the orbit of the chaser using an electric thruster. The phasing mission ends when these two spacecraft rendezvous successfully.

Under the assumption that the chaser and target spacecraft move in the same plane, no out-of-plane thrust component is considered in this instance. The variational form of the classical orbital elements problem for the chaser can be described as [3]

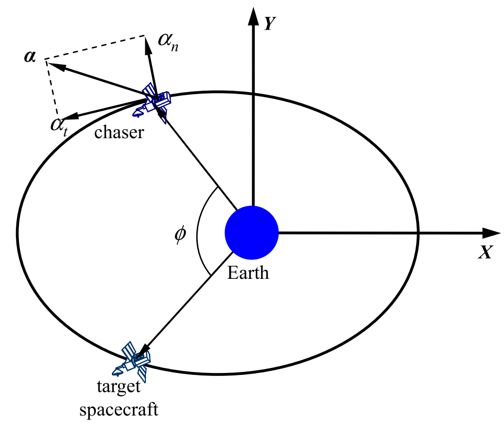

Fig. 1. The geometry of the orbital phasing problem.

$$\begin{cases} \dfrac{da}{dt} = \dfrac{2a^2 v}{\mu}\alpha_t \\ \dfrac{de}{dt} = \dfrac{1}{v}\left[2(e+\cos\theta)\alpha_t - \dfrac{r}{a}\sin\theta\alpha_n\right] \\ \dfrac{d\omega}{dt} = \dfrac{1}{ev}\left[2\sin\theta\alpha_t + \left(2e+\dfrac{r}{a}\cos\theta\right)\alpha_n\right] \\ \dfrac{dM}{dt} = n - \dfrac{\sqrt{ap}}{eav}\left[2\left(1+\dfrac{e^2 r}{p}\right)\sin\theta\alpha_t + \dfrac{r}{a}\cos\theta\alpha_n\right] \\ \dfrac{dm}{dt} = -\dfrac{T}{gI_{sp}}, \end{cases} \tag{1}$$

where a is the semi-major axis, e is the eccentricity, ω is the argument of the periapsis, θ is the true anomaly, M is the mean anomaly, p is the semilatus rectum, r is the orbital radius, and $n = \sqrt{\mu/a^3}$ is the mean motion, m is the mass of the spacecraft, T is the thruster thrust magnitude, g is the gravitational acceleration at sea level, and I_{sp} is the thruster's specific impulse. The gravitational parameter of Earth is denoted by μ. The thrust acceleration vector is defined by the components $\boldsymbol{\alpha} = [\alpha_t, \alpha_n]^T$ as follows:

$$\boldsymbol{\alpha} = \frac{T}{m}\boldsymbol{u} = \frac{T}{m}\begin{pmatrix} u_t \\ u_n \end{pmatrix}, \tag{2}$$

where $\boldsymbol{u}$ is the unit vector in the thrust direction.

It is noted that the target spacecraft moves according to Keplerian motion. Therefore, only the variation of the mean anomaly needs to be considered. A general problem statement for the orbital phasing maneuver design problem can be given as follows:

Find the initial phasing time t_0, the duration of the powered arc of the chaser, t_p, and the thrust direction vector for the powered arc, $\boldsymbol{\alpha}(t)$ which minimize:

$$\boldsymbol{J} = t_f - t_0, \tag{3}$$

where t_f is the rendezvous time.

The initial mean anomaly of the chaser and target spacecraft are defined as M_{C0} and M_{T0}, respectively. At the end of the phasing segment, the states of the chaser should satisfy the following terminal constraints:

$$\boldsymbol{\chi}_1 = \begin{pmatrix} a_C(t_f) - a_T(t_f) \\ e_C(t_f) - e_T(t_f) \\ \omega_C(t_f) - \omega_T(t_f) \\ M_C(t_f) - M_T(t_f) \end{pmatrix} = 0, \tag{4}$$

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